DEPARTMENT OF THE INTERIOR—U. S. GEOLOGICAL SURVEY
J. W. POWELL DIRECTOR

SKETCH OF THE GEOLOGICAL HISTORY OF LAKE LAHONTAN

A QUATERNARY LAKE OF NORTHWESTERN NEVADA

BY

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CONTENTS.

ILLUSTRATIONS.

SKETCH OF THE GEOLOGICAL HISTORY OF LAKE LAHONTAN.*

By I. C. Russell.

INTRODUCTION.

During the field season of 1881 the writer traveled through northwestern Nevada and some portions of California and Oregon for the purpose of studying the Quaternary geology. The journey was purely a geological reconnoissance, his companions including no scientific assistants, and all instrumental work being deferred until another season, when a more detailed study and survey of the points of special interest could be made. During the field season of seven months, about three thousand five hundred miles were traversed in the saddle, the route being planned with special reference to the investigation of the more recent geological changes, or of those most directly concerned with the present surface features of the country.

The most interesting results of the reconnoissance were, the discovery of a number of fossil lakes of Quaternary age in a land that is now extremely arid, and the acquisition of many new facts in regard to other extinct lakes that had previously been reported. Of the lakes that occupied many of the valleys of northern Nevada during Quaternary times, by far the most interesting, as well as the largest, was Lake Lahontan; and as this affords the most complete record of Quaternary climatic oscillations, we have chosen it as the subject of our present sketch, leaving the consideration of the smaller lakes, many of which have interesting histories, for a more extended report.

Before studying the geology of any region it is always desirable to know something of its present condition, and especially of the peculiar features of climate and geography that characterize it. For this reason we shall preface the description of the Quaternary lakes by a brief sketch of the Great Basin as the explorer finds it to-day.

* This paper was written by Mr. Russell in camp, while continuing the study of the same subject. Having no access to books he was unable to make the references he desired to the work of others, and lack of time compelled him to leave the manuscript in a somewhat unfinished condition. It was moreover impracticable for him to correct proof-sheets. At his request the paper was revised and edited by me, so that I share with him the responsibility for many of the details.—G. K. Gilbert.

THE GREAT BASIN.

In crossing fromthe Atlantic to the Pacific, between the Mexican boundary and the central portion of Oregon, one finds a region, bounded by the Sierra Nevada on the west and the Rocky Mountain system on the east, that stands in marked contrast in nearly all its scenic features with the remaining portions of the United States. The traveler in this region is no longer surrounded by the open, grassy parks and heavily timbered mountains of the Pacific slope, nor by the round and flowing outlines of the forest-crowned Appalachians. Neither does the scenery suggest aught of the boundless plains east of the Rocky Mountains, or of the rich savannas of the Gulf States. He must compare it rather to the parched and desert areas of Arabia and the shores of the Dead Sea and the Caspian.

To the geographer the most striking characteristic of the country along the eastern base of the Sierra Nevada is the fact that it is a region of interior drainage. For this reason it is known as the "Great Basin." No streams that rise within it carry their contributions to the ocean, but all the rain that falls inside the rim of the basin is returned again to the atmosphere, either by direct evaporation from the soil, or after finding its way into some of the lakes that occupy the depressions of the irregular surface. The climate is dry and arid in the extreme, the average yearly rainfall probably not exceeding 12 or 15 inches.

The area thus isolated from the water systems of the world is 800 miles in length from north to south, and nearly 500 miles broad in the widest part, and contains not far from 208,500 square miles—an area somewhat greater than that of France. The southern part of the region includes the Colorado Desert, Death Valley, and much of the arid country in southern California and Nevada. In northern Nevada the Carson and Black Rock deserts exhibit the extreme of desolation. The most northerly part of the Great Basin, occupying the central portion of Oregon, is less barren, its rugged surface abounding in volcanic table lands and isolated mesas, weathering as they grow old into rounded buttes that are covered with luxuriant bunch grass and bear a scattered growth of cedars and pines. At the south the valleys of the Great Basin are low-lying, Death and Coahuila valleys being depressed below the level of the sea; but at the north the valleys have a general elevation of from 4,000 to 5,000 feet, while the intervening mountain ranges rise from 5,000 to 7,000 feet above them.

Diversifying this region are many mountain ranges and broad desert valleys, together with rivers, lakes, cañons, etc.—topographic elements to be found in all quarters of the world, but here characterized by features peculiar to the Great Basin. The mountains exhibit a type of structure not described before this region was explored, but now recognized by geologists as the "Basin Range structure." They are long, narrow ridges, usually bearing nearly north and south, steep upon one

side, where the broken edges of the composing beds are exposed, but sloping on the other with a gentle angle conformable to the dip of the strata. They have been formed by the orographic tilting of blocks that are separated by profound faults, and they do not exhibit the anticlinal and synclinal structures commonly observed in mountains, but are monoclinal instead.

The valleys or plains separating the mountain ranges, far from being fruitful, shady vales, with meandering streams, are often absolute deserts, totally destitute of water, and treeless for many days' journey, the grayish-green *Artemisia* or "sage bush" giving character to the landscape. Many of them have playas in their lowest depressions—simple mud plains left by the evaporation of former lakes; and sometimes these playas are of vast extent. In the desert bordering Great Salt Lake on the west, and in the Black Rock Desert of northern Nevada, are tracts hundreds of square miles in area, showing scarcely a trace of vegetation. In the summer months portions of them become so baked and hardened as scarcely to receive an impression from a horse's hoof, and so suncracked as to resemble tessellated pavements of cream-colored marble. Other portions of the valleys become incrusted to the depth of several inches with alkaline salts, which rise to the surface as an efflorescence and give the appearance of drifting snow. The dry surface material of the deserts is sometimes blown about by the wind, saturating the air, or is caught up by whirlwinds and carried to a great height, forming hollow columns of dust. These swaying and bending columns, often two or three thousand feet high, rising from the plains like pillars of smoke, are a characteristic feature.

The rivers of the Great Basin are not all perennial; some of them disappear before the heat of summer. In the streams that are perennial a high percentage of the annual discharge is crowded into a brief space toward the end of the rainy season. Thus the arteries of this parched and heated country make but one feverish pulsation in a year. The streams usually diminish in volume as they descend into the valleys, and in many instances their waters are lost on the thirsty deserts and their channels run dry. In general they are larger near their sources than at their mouths. Commonly, too, instead of being pure, sparkling waters, refreshing to the lips as well as the eye, they are heavy with sediment and bitter and alkaline to the taste.

The lakes into which much of the surface drainage finds its way are commonly saline and alkaline—their shores a desert waste, shunned by animals and by all but salt-loving plants. Of the salt lakes the typical example is furnished by Great Salt Lake in Utah, an inland sea whose features call to mind the familiar descriptions of the Dead Sea in Palestine. Mono Lake in California, and Abert and Summer lakes in Oregon, are also highly charged with saline matter, and are remarkable for the amount of carbonate of soda they contain. Pyramid, Walker, Winnemucca, and Carson lakes, in Nevada, as well as many

smaller lakes throughout the Great Basin, are also without outlet, yet hold comparatively small percentages of saline matter in solution.

Other lakes, which indicate still more pointedly the contrast between an arid and a humid climate, we may call *playa lakes*. These are broad sheets of shallow water, covering many square miles in the winter season, but evaporating to dryness during the summer, their beds becoming hard, smooth mud plains or playas. In many instances a lake is formed over a playa during a single stormy night, only to disappear beneath the next noonday sun. When the weather is unsettled these lakes are scarcely more permanent than the delusions of the mirage, but come and go with every shower that passes over the land. Other playa lakes are more persistent, and only become dry during excessively arid seasons. Examples of these are furnished by Honey Lake in California, North Carson Lake ("Carson and Humboldt Sink") in Nevada, and Sevier Lake in Utah, all of which have been known to become dry during the past few years. The water of playa lakes has a greenish yellow color, due to the extremely fine silt which is held in suspension and not allowed to settle, because every breeze stirs the shallow water to the bottom. A remarkable lake of this class is sometimes formed on the northern part of the Black Rock Desert during extremely wet seasons. Its water is furnished by Quinn River, and it has been known to have a length of 50 or 60 miles, with a breadth of 20. During the summer it disappears entirely, leaving an absolutely barren plain of mud, Quinn River at the same time shrinking back a hundred miles toward its source.

A few lakes situated on the borders of the Great Basin have outlets, and discharge their surplus waters into reservoirs at lower levels within the area of interior drainage. These lakes are of the same type as the ordinary lakes of humid climates, with waters as pure and fresh as springs and melting snow can furnish. Their finest example, Lake Tahoe, lies just within the western rim of the Great Basin, at an elevation of 6,247 feet, amid the peaks of the Sierra Nevada. Its outlet, the Truckee River, flows downward with a descent of 2,400 feet to Pyramid and Winnemucca lakes, where the water is evaporated, leaving the lower lakes charged with soda salts. Just within the eastern border of the Great Basin lie Bear Lake and Utah Lake, the former discharging its water through the Bear River and the latter through the Jordan River into Great Salt Lake. These streams carry down from the mountain their small percentages of saline matter, as a contribution to the already saturated solution of the inland sea where their waters are evaporated.

It may be taken as a rule, that all lakes which overflow are fresh, and all lakes that do not find outlet become in time charged with mineral salts. The explanation of the salinity lies in the fact that river water is never absolutely pure, but always contains a small percentage of mineral matter, which is left behind when the water is evaporated.

Should this process continue long enough it is evident that a lake without an outlet would in time become a saturated solution, from which the less soluble mineral salts would begin to crystallize.

The examination of those inclosed lakes of the Great Basin that are comparatively fresh, and especially of the lakes occupying the Lahonton Basin, shows that salt lakes may become fresh without overflowing; and it has been suggested by Mr. Gilbert, in explanation, that a lake may evaporate to dryness and its salts become buried beneath the deposits of playa lakes, so that on the return of humid conditions the water that re-occupies the old basin may be comparatively if not absolutely fresh.

To the artist the scenery of the arid lands of the Far West is contrasted with that of more humid regions by the russet brown desolation of the valleys, the brilliant colors of the naked rocks, and the sharp, angular outlines of the mountains. A country without rain is necessarily a desert, while with abundant moisture, at least in tropical and temperate latitudes, it becomes a garden of luxuriant vegetation. In the most desert portions of the Great Basin the annual precipitation probably does not exceed 4 inches, while in the valleys on the borders of the basin it reaches 20 or 30 inches. Throughout this region the only fruitful areas are along the margins of streams or where springs come to the surface. In such places, water being available for irrigation, one finds oases of delicious shade, with green fields and orchards, yielding an unusually abundant harvest. Thus in nearly all its physical features the Great Basin stands in marked contrast with those favored lands where rain is more abundant and more evenly distributed.

The rainfall that a region receives is a potent though silent factor, controlling an almost infinite series of results in its physical history and topography. In a humid region vegetation is usually luxuriant; the rock forms are masked by forests, erosion is rapid, and the rocks are commonly buried beneath the accumulations of their own *débris* or concealed by layers of vegetable and animal mold that in turn are clothed with vegetation; the hills have flowing outlines and are dark with foliage; the valleys have gently sloping sides that conduct the drainage into streams meandering through broad plains, and the whole scene has the softness and beauty of a garden. In an arid land like the Great Basin all this is changed. The mountains are rugged and angular, are for the most part unclothed by vegetation, and receive their color from the rocks of which they are composed. From the gorges and cañons sculptured in the mountain side alluvial cones descend to the plain. These sometimes have an extent of several miles, and they are steep or gentle in slope according to the grade of the streams that formed them. The valleys, even more dreary than the mountains, are without arboreal vegetation and without streams, and form a picture of desolation and solitude. In traveling through the Great Basin one sometimes rides a hundred miles without sight of a

tree, and many times that distance without finding shade enough to protect him from the intense summer sun.

The bare mountains reveal their structure almost at a glance, and show distinctly the many varying tints of their naked rocks. Their richness of color is sometimes marvelous, especially when they are composed of the purple trachytes, the deep-colored rhyolites, or the many-hued volcanic tuffs so common in western Nevada. Not unfrequently a range of volcanic mountains will exhibit as many brilliant dyes as are assumed by the New England hills in autumn. On the desert valleys the scenery is monotonous in the extreme, yet has a desolate grandeur of its own, and at times, especially at sunrise and sunset, great richness of color. At midday in summer the heat becomes intense, and the mirage gives strange delusive shapes to the landscape and offers promises of water and shade where the experienced traveler knows there is nothing but the glaring plain. When the sun is high in the cloudless heavens and one is far out on the desert at a distance from rocks and trees, there is a lack of shadow and an absence of relief in the landscape that make the distance deceptive—the mountains appearing near at hand instead of leagues away—and cause one to fancy that there is no single source of light, but that the distant ranges are self-luminous. The glare of the noonday sun conceals rather than reveals the grandeur of this rugged land, but in the early morning and near sunset the slanting light brings out mountain range after mountain range in bold relief and reveals a world of sublimity. As the sun sinks behind the western peaks and the shades of evening grow deeper and deeper on the mountains, every ravine and cañon becomes a fathomless abyss of purple haze, shrouding the bases of gorgeous towers and battlements that seem incrusted with a mosaic more brilliant and intricate than the work of the Venetian artists. As the light fades and the twilight deepens, the mountains lose every detail and become sharply outlined silhouettes, drawn in the deepest and richest of purple against a brilliant sky.

The succession of seasons is less plainly marked on the deserts of the Great Basin than on the forest-covered hills of the Atlantic slope. As autumn advances, but little change appears in the color of the landscape, excepting, perhaps, a spot here and there of vermilion or carmine high up on the mountains, where a clump of aspens or dwarfed cedars marks the site of a spring that trickles down and loses itself among the rocks. The valleys with their scanty growth of sage remain unchanged, as do the dusky bands of pines and cedars on the higher mountains. As the autumn passes away the skies lose their intense blue, and become softer and more watery—more like the skies of Italy. The hues of sunset appear richer and more varied, and during the day cloud masses trace moving lines of shadow on the surface of the desert. By and by storm clouds gather in black, gloomy masses that envelop the ranges from base to summit. These early storm clouds cling close

to the mountains and yield to the parched deserts but a few scattered drops of rain. The observer from below hears the raging tempest amid the veiled peaks, while all about him is sunshine. The mountains wrapped in impenetrable clouds, the glare of lightning, and the deep roll of thunder as it echoes from cliff to cliff and from range to range, bring to mind the scriptural account of the storms of Sinai. And when the black clouds at last roll back from the mountains, and the sun with a wand of light dispels the storm, behold what a transfiguration! The peaks are no longer dark and somber, but glitter with the silvery sheen of freshly fallen snow.

As winter approaches, the storms amid the uplands become more frequent, until every range is white as snow can make it, and the tent-like mountains gleam like the encampment of some mighty host. Long after they are covered the valleys between are bare as in midsummer, and the snow seldom lies in them for more than a few days at a time. The highlands retain their snow far into the summer, but on none of the ranges can it be said to be perpetual. In the valleys there are flowers beneath the sage-brush by the middle of April, and from that time until November scarcely a drop of rain falls. For many days together the skies are without a cloud.

The agriculture of this arid region is restricted to those scanty areas of land that can be irrigated. Of more importance is the grazing of sheep and cattle on the bunch-grass that frequently abounds in the mountains and sometimes grows luxuriantly beneath the sage-brush. The mines of the precious metals, however, are the principal source of wealth, and to that must now be added a growing industry in salt, borax, sulphur, and carbonate of soda.

Although the Great Basin is not attractive to the pleasure-seeker, yet to the geologist it is peculiarly fascinating, both because the absence of vegetation gives such unusual facilities for investigation and because of the interesting character of the problems to be solved. In this inhospitable region, so arid that many a lost traveler has perished from thirst, there existed in recent geological times a system of great lakes, comparable in number and magnitude with the lakes of the Saint Lawrence basin. At the time New England and a number of the Northern States were covered with an immense *mer de glace*, and the lofty peaks of the Rocky Mountains, the Sierra Nevada, and a few of the intermediate ranges, gave birth to local glaciers, the ratio of precipitation to evaporation throughout the Great Basin was so great as to give rise to a great number of lakes, whose combined surface must have formed a large percentage of the total area of the region. Twenty-one of these ancient lakes, of which Lake Bonneville and Lake Lahontan are the most interesting, have already been explored in the northern part of the basin, and at least three of some magnitude are known to have existed at the south.

Although the Great Basin is an extensive area of interior drainage,

it is far from being a simple basin-shaped depression in form. It is broken and diversified by many mountain ranges, which divide the surface into numerous separate drainage areas or hydrographic basins. These subsidiary basins held the Quaternary lakes. They owe their origin almost invariably to orographic displacements, and, like the intervening mountains, exhibit a type of structure that is peculiar to the region. In many instances, one edge of a long and narrow orographic block is upraised along a fault line so as to form a lofty mountain range, while the depressed edge underlies a valley that constitutes an inclosed lake basin. Like the Basin ranges, the Basin valleys have faults along their edges, one or both, and are commonly monoclinal.

The Basin Range structure, as it appears along a large number of east and west sections, is rudely shown in the accompanying diagram, in which the upraised edges of the orographic blocks form mountain ranges, and the depressions are represented as occupied by lakes or as deeply filled with lake sediments and alluvium from the mountains.

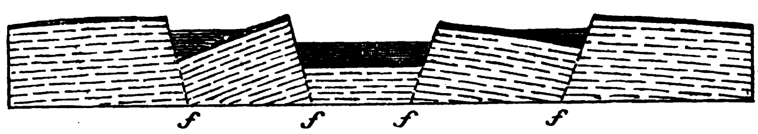
W  E

FIG. 44.—Ideal section illustrating Basin Range structure.

At *f*, *f*, *f*, *f*, are represented faults that have divided the country into long, narrow blocks, with a north and south trend, and these blocks are represented as displaced and tilted at various angles. The depression formed by the fault at the left may be taken as a rude generalized expression of Surprise Valley, California, which once held a lake nearly a hundred miles long, and is now deeply filled with lake-beds. The central depression represents rudely the structure of Christmas Lake Valley, Oregon, with its great fault scarps from 1,500 to 2,000 feet high on either side. Instances could be multiplied almost without number from all parts of the Great Basin, of valleys once occupied by Quaternary lakes and having this same type of structure.

Lake Bonneville and Lake Lahontan each occupied many valleys of this type. The former extended along the western base of the Wasatch Range for 300 miles, its northern extremity reaching a few miles into Idaho, its surface covering 19,750 square miles, and its hydrographic basin having an area of 52,000 square miles. The latter, named by Mr. King in honor of the French explorer,* lay on the western side of the Great Basin, and was of nearly as great extent. The hydrographic basins of these two great Quaternary lakes occupied the whole breadth of the Great Basin in the latitude of the 41st parallel.

* Reports of the Fortieth Parallel Survey, vol. I, p. 504.

LAKE LAHONTAN.

GEOGRAPHIC EXTENT.

The principal body of Lake Lahontan lay in what is now northwestern Nevada, but a small arm occupied Honey Lake Valley in California. From a point a few miles north of the Oregon boundary it extended southward 260 miles to latitude 38° 30′, and it had its greatest width a little north of the 40th parallel. As may be seen in the accompanying map it was extremely irregular in outline, more irregular in fact than any other lake, recent or fossil, that has been mapped. Perhaps the most peculiar feature of its geography is the irregular island it inclosed, 126 miles long from north to south by 50 miles broad. This bore a number of lofty and rugged mountain ranges, and held in its interior two small lakes, neither of which outflowed into the surrounding lake. Of the subordinate bodies of water which united to form Lake Lahontan the two largest covered the Carson and Black Rock deserts respectively, being connected with each other by narrow straits. One connecting arm occupied the valley of Pyramid Lake, and extending through the cañon now traversed in part by the Truckee River joined the Carson area through the Ragtown Pass; the other stretched from the Carson Desert northward up the Humboldt Valley, and then ran to the west of the Eugene Mountains until it joined the northern end of the Black Rock area in Quinn River Valley.

The evaporation of its water has left the old lake basin divided into a number of comparatively small hydrographic areas, of which the principal ones are now occupied by lakes. The modern lakes are Pyramid, Winnemucca, Humboldt, North Carson, South Carson, and Walker, all of Nevada, together with Honey Lake in California. All of these are more or less saline or alkaline, but in no instance are they concentrated brines, as would be the case were they the remnants left by the incomplete evaporation of Lake Lahontan.

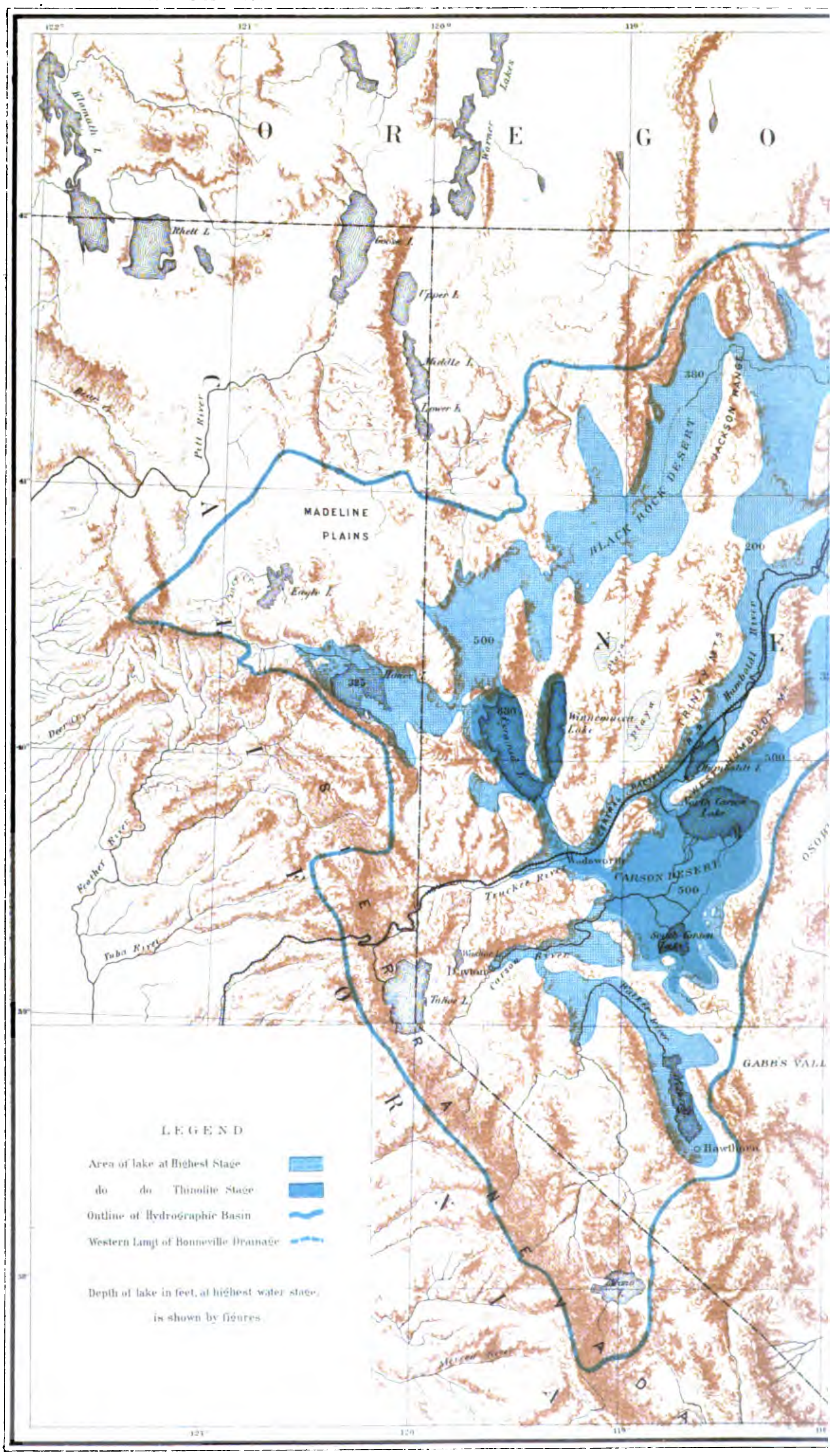
The Central Pacific Railroad passes for 165 miles through the desiccated bed of the extinct lake, entering it a few miles east of Golconda by the cañon through which the Humboldt River traverses the Sonoma Mountains, and leaving it on the west in the cañon of the Truckee River about 15 miles west of Wadsworth. While passing down the valley of the Humboldt from Golconda to Humboldt Lake, one may see from the train the sedimentary beds deposited by the waters of the former lake. They are exposed in the cliffs of clay and marl that border the river,

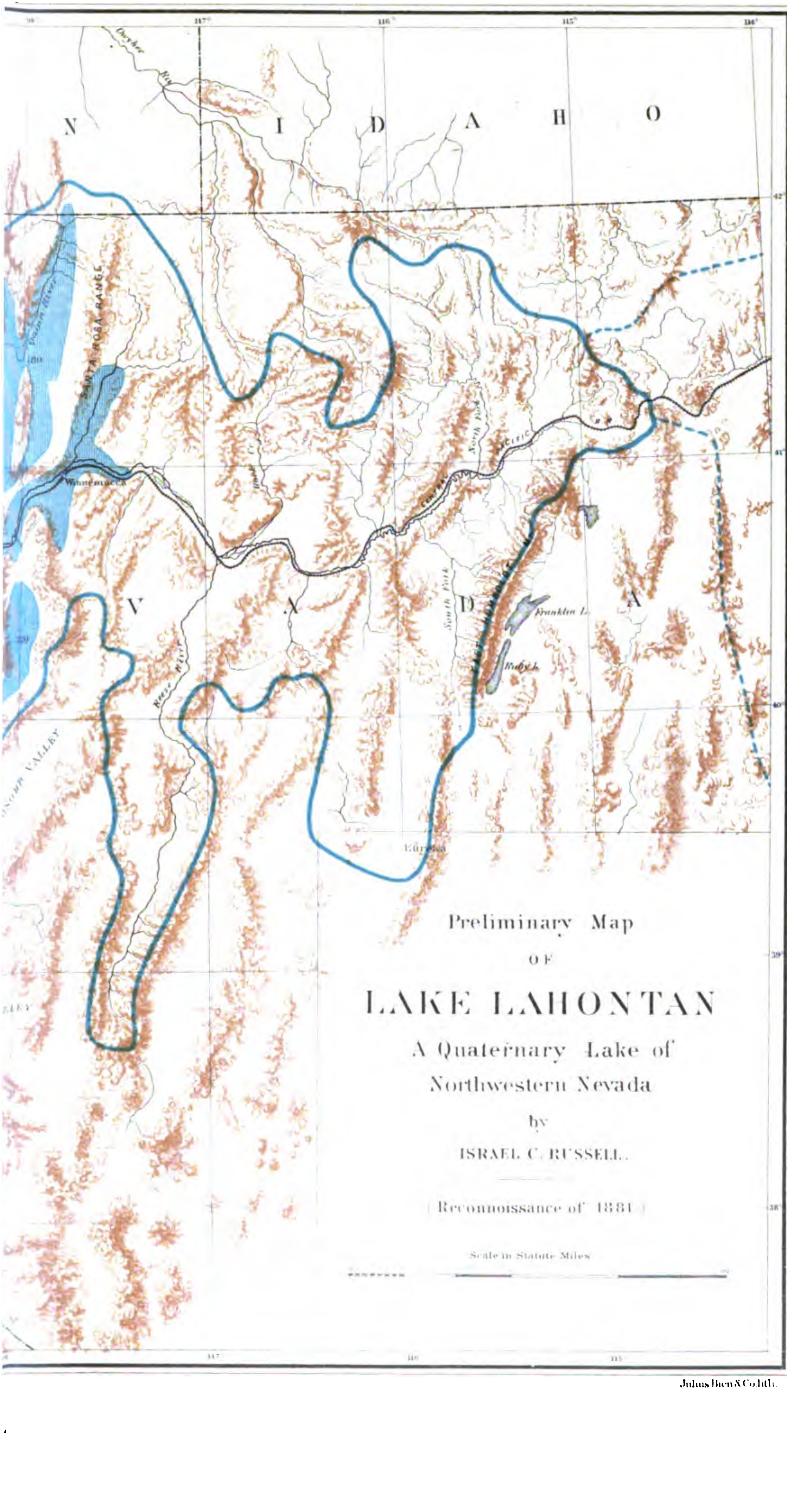
and the height of these cliffs, which in places amounts to 150 or 200 feet, exhibits the amount of erosion performed by the river since the evaporation of the lake. The horizontal lines carved by the waves of the lake on the steep shores that confined it, may likewise be traced by the passenger all along the bases of the mountains on either hand. Between Humboldt Lake and Mirage Station the traveler has a glimpse out onto the broad Carson Desert to the southward, at one time covered by the waters of Lake Lahontan to a depth of 500 feet, but now an absolute desert. At Wadsworth the train descends into the cañon excavated by the Truckee River through the old delta that was formed by the same stream when Lahontan filled this portion of the valley and received the *débris* brought down from the Sierra. Sections of the Truckee delta and of Lahontan lake-beds are well exposed in the river bluffs north of Wadsworth, and synchronous strata may also be seen clinging in fragmental masses to the rugged sides of the cañon for a distance of 15 miles west of the station. The lake-beds are here easily distinguished, by their light color and horizontal stratification, from the dark volcanic rocks against which they rest.

The rim of the hydrographic basin of which Lake Lahontan received the drainage, scarcely more regular in outline than the lake itself, is indicated on the accompanying map by a heavy blue line. On the west it coincides with the rim of the Great Basin, and is formed by the crest of the Sierra Nevada. Along this high divide, at the time Lahontan had its greatest extent of surface, there were four lakes of considerable size that overflowed into it. Beginning at the south we have, first, Mono Lake, in regard to whose outlet, however, there is some doubt; second, Lake Tahoe, at that time surrounded by glaciers; third, the little lake filling Washoe Valley; and fourth, a lake, since drained dry, that covered the Madeline Plains, in Lassen County, California. The extent of the hydrographic basin is shown by the river systems compassing it. These were Walker, Carson, and Truckee rivers on the west, Quinn River on the north, and the Humboldt and Reese rivers on the east. All of these streams at that time flowed with somewhat greater volume than at present. From the desert region at the southeast no tributaries were received. The area of the drainage basin was about 45,400 square miles, and the ratio of lake surface to drainage area was nearly as 1 to 5.

TOPOGRAPHY OF THE LAHONTAN SHORES.

We have said that a number of valleys of northwestern Nevada were at one time occupied by the waters of a large lake. It is natural for the reader to ask how we know this, and what kind of evidence we have to prove our statement. In reply we would say that the evidence by


O R E G O N
Klamath L.
Rhett L.
Goose L.
Warner Lakes
Upper L.
Middle L.
Lower L.
Pitt River
MADELINE
PLAINS
Eagle L.
Honey L.
Deer Cr.
Feather River
Yuba River
Pyramid L.
Winnemucca Lake
BLACK ROCK DESERT
JACKSON RANGE
Humboldt River
Humboldt L.
North Carson Lake
CARSON DESERT
South Carson Lake
Wadsworth
Truckee River
Carson River
Walker River
Walker L.
Tahoe L.
Hawthorne
Mono L.
GABB'S VALL
SIERRA NEVADA
380
200
500
385
530
LEGEND
Area of lake at Highest Stage
do do Thinolite Stage
Outline of Hydrographic Basin
Western Limit of Bonneville Drainage
Depth of lake in feet, at highest water stage, is shown by figures



Julius Bien & Co lith.

which we determine that a valley was at one time occupied by a lake is of the same nature as that which leads us to conclude when we walk along an ocean shore that the tide is high or that it is low.

Again, if a mill-pond be drained by the opening of its gates we have no difficulty in determining how deep the pond was when its waters filled it. We find a little terrace or ridge of sand and gravel all about the horizontal line where the surface of the lake met its shores. This terrace and this ridge are shore records. Throughout the little basin once filled by the pond we find a deposit of mud, which is simply the dirt and silt brought in by the inflowing rills and rivulets. To the geologist this deposit is a lake-bed. In the layers of mud at the bottom of the pond we usually find the shells of fresh-water mollusks, and perhaps also a few bones of fishes or of land animals, or maybe a buried branch or twig. These are fossils, and illustrate the character of the animals and plants that lived in and about the pond. And finally, at the point where each rill and rivulet from the hills entered the pond we find a fan-shaped accumulation of sand and gravel, constituting a delta with all the essential features of the delta of the Nile or of the Mississippi.

Turning now to the valleys of northwestern Nevada, if our conclusion that they were once filled by a lake is correct, it is clear that we should find terraces, lake-beds, fossils, and deltas—the same records, in fact, that may be seen to-day in every mill-pond, but on a grander scale. In the case of Lake Lahontan all of these proofs, and more besides, have come under our observation. The entire shore line, intricate and tortuous as it is, has been followed and mapped in the field, and it is to the character of this shore line that we now invite attention.

As has been remarked by Mr. Gilbert, "there is a topography of the land and a topography of the sea." The topography of the land is due to the beating of the rain, the expansive action of frost, the flow of rills and rivers, and so forth. The slopes of the valleys and ridges that these agencies carve on the mountain side are controlled by the flow of water in response to gravity, and the lines thus formed are therefore more or less inclined. The topography of the shores of oceans and lakes exhibits the lines carved by waves where they beat against the land; these lines conform to the water surface, and are horizontal.

Throughout the boundaries of Lake Lahontan its ancient shore line is clearly defined. The sloping sculpture of rain and rills above, and the horizontal lines due to wave action along the base of the mountains, afford a contrast that is noticeable at a glance. The fact that these shore lines are continuous all about the borders of the former lake, and are not cut by a channel of overflow, proves that the lake never found an outlet. The multitude of beach lines scoring the mountain bases also indicate that the lake underwent many fluctuations of level—rising and falling, as do all inclosed lakes. Each individual shore line marks a pause in the fluctuations of level of the surface, and the relative duration

of the various pauses is indicated to some extent by the width of the wave-cut terraces, the magnitude of the embankments built at different horizons, and the thickness of the contemporaneous sediments accumulated at the bottom of the basin. By the state of these various phenomena we are enabled to decipher at least a portion of the Lahontan history, and learn something of the climatic changes on which that history depended.

THE FORMATION OF TERRACES AND EMBANKMENTS.

The tendency of waves washing against a shore is to cut away the rocks so as to form a terrace or gently sloping shelf, bounded on the landward side by a steep escarpment or sea cliff. The accompanying diagram shows the profile of a shore against which the waves break, and will illustrate the character of the notch the waves carve.

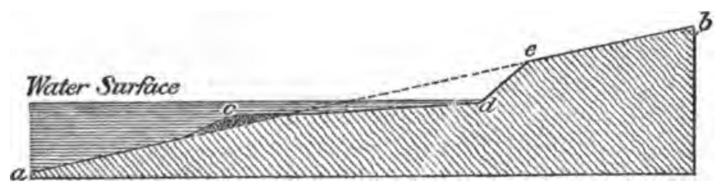


FIG. 45. Profile of Terrace and Sea Cliff.

In the diagram the line *a b* represents the original slope of the shore (it may be of alluvium or of solid rock), in which the waves have excavated the terrace *c d*, forming at the same time the steep sea cliff *e d*. The outer portion of the terrace at *c* is commonly formed of *débris* from the cutting of the terrace. The steepness of the sea cliff, and to a less degree the slope of the surface of the terrace, depend on the nature of the material composing the shore.

When the wind acting on the water of a lake causes the waves to advance at right angles to the shore, the water rushes up the gently inclined surface of the terrace, carrying with it a load of the sand and loose pebbles that come within its reach, and thus freighted it dashes against the shore and grinds away the base of the sea cliff. As the water returns to the lake, forming an undertow, the stones roll back down the terrace and the finer material is carried to the outer edge of the slope, or perhaps into deep water. This sapping of the sea cliff goes on until portions are undermined and fall away, their *débris* adding to the supply of tools with which the water works. When the waves break against a shore at any angle except a right angle a shore current is established, and the action of waves and currents combined proves still more efficient in carving away the land. In some instances, as on

the eastern coast of Australia, the wave-cut terraces are nearly a mile broad. In the Quaternary lakes of the Great Basin they were frequently several hundred feet wide, with sea cliffs rising above them several hundred or even a thousand feet.

If we stand on a gently sloping lake shore when a strong wind is blowing against the beach at any angle, say 30° for illustration, we find that a current is soon established along the shore which moves a quantity of loose material with it, the waves lifting the pebbles and stones and the current carrying them along. This sheet of sand and gravel traveling along a shore has been designated *shore drift*. To the transportation of shore drift, and to its eventual deposition, we owe the most striking and interesting of shore phenomena, namely, shore embankments. The cutting of a terrace with its overhanging sea cliff is a work of excavation—the *carving* of a new form on a pre-existing surface; the topographical features produced by the accumulation of shore drift are works of construction, consisting of embankments of various forms *superimposed* on the pre-existing topography.

A current sweeping along a shore carries with it, as we have described, a narrow sheet of shore drift. On shores of moderate inclination this material forms a terrace of gravel that is not infrequently adjoined to a cut terrace, forming a sort of platform—the highway for the transportation of the shore drift. On a low shore of alluvium the tendency is to form a bar or embankment with rounded crest, parallel to the shore, and at some distance from the actual water margin. Such an accumulation is known as a *barrier*. When the current comes to an angle of the coast,

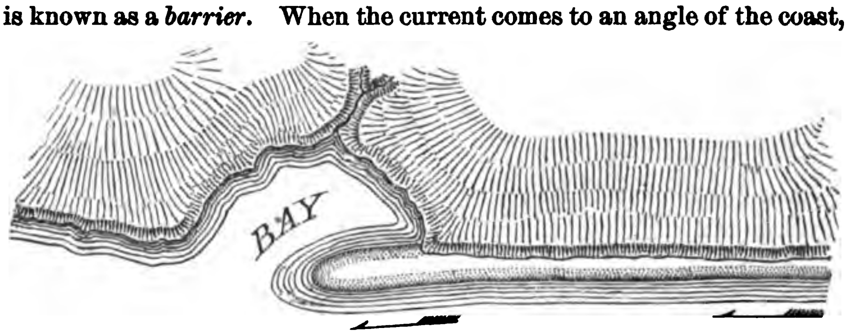


FIG. 46.—Ideal plat illustrating the formation of a Shore Embankment.

as, for example, the mouth of a bay, it does not follow the sinuosities of the water line, but holds the trend previously established, and sweeps its load of shore drift forward into deeper water, where the force of the current is soon lost and the *débris* deposited at the bottom. Other material is piled upon that first deposited until an accumulation or embankment is formed that reaches nearly to the surface, and constitutes a continuation of the shore terrace along which the drift had previously been carried. This accumulation of *débris* has the form of a railroad embankment, and forms a path for the transportation of fresh material. This, in its turn, is carried to the end of the embankment and serves to prolong the structure.

The action of shore currents in building out embankments is illustrated by the accompanying topographical diagram. The dotted surface represents the limit of the shore drift, and the arrows show the direction of the current as it follows the shore. On arriving at the entrance to the bay, where the shore makes an abrupt turn, the current continues directly onward, carrying the shore drift with it and building out the embankment. In a simple instance like that of the illustration the embankment is straight, with a rounded extremity. This extremity is bounded beneath the water surface by a steep escarpment, the angle of the slope being the angle of stability in water of the material of which the structure is composed. At times the distal end of such an embankment is curved, and forms a hook bending into the bay. Again it may be carried completely across the bay, thus shutting it off from the lake and forming a lagoon. Being constructed chiefly during storms, embankments have their crests a little above the surface of the lake at its ordinary stage.

The action of waves and currents that conspire to form embankments like that shown in the sketch is subject to a multitude of variations, depending on the topography of the shore, on changes in the direction of the wind, and on the nature of the material moved; and, as may be imagined, the resultant forms are extremely diverse. When the lake is likewise subject to great fluctuations of level the embankments are superimposed one upon another and frequently form complicated structures of great size. Sometimes, too, an embankment that has been built during a high-water stage is cut away by subsequent wave action at lower levels, and its material remodeled.

It is to be remembered that the ability of waves and currents to modify shores depends largely on the sand and pebbles forming the shore drift. Where the shore is steep it is evident that the cutting power of the water is small, since nearly all the sand and pebbles fall into deep water beyond the reach of the waves and cannot be used as cutting tools. In such places we find narrow terraces with high sea cliffs. Where the water stands against a perpendicular wall its cutting power is at zero. Again, where the shores are only moderately steep the cutting of a terrace goes on rapidly, the *débris* being carried forward to form embankments where the shore becomes less steeply inclined or where the material is thrown into deep water. The alternation of these two conditions along the margin of a lake seems most favorable for the production of a conspicuous shore topography. Where we find heavy embankments of gravel formed by an accumulation of shore drift, we may look for the quarry from which the material was derived along the terraced slopes near at hand.

In Lake Lahontan the coasts were moderately steep, and the most common of the surviving shore records are cut terraces. From the highest water line down to the bottom of the basin, as it now exists, the surface is scored by a large number of horizontal terraces. Examples of

embankments of gravel formed in the manner just described may also be seen at many places along the ancient borders of the lake; but all these phenomena are less finely displayed than in the Bonneville basin, where the water was deeper and the stretches of open water were broader.

The features in the shore records of Lake Lahontan that are most strongly accented are, first, the highest water line of all, showing the maximum depth of the old lake; second, a broad, sharply cut terrace about 30 feet below the highest water line; and third, a broad terrace about 400 feet lower than the last, or 100 feet above the present (1881) level of Pyramid Lake. For reasons which will appear in the sequel the second of these has been named the *Lithoid*, and the third the *Thinolite* terrace. The highest terrace of all, the *Lahontan*, is an inconspicuous feature in itself, but is important as forming the boundary between subaerial and subaqueous sculpture in the sides of the valleys. It usually appears as a terrace of construction a few feet wide, resting on the broad Lithoid terrace 30 feet below. Where the shore records are unusually well preserved, as along the western margin of Pyramid Lake and on the south side of the Carson Desert, the Lithoid terrace sometimes has a width of 200 or 300 feet. Resting on it we sometimes find two built terraces of gravel and rolled stones, the water line of the one being the highest of all the shore records, while the second is intermediate between that and the Lithoid terrace. This arrangement is illustrated in the accompanying diagram, which exhibits a profile of the shore.

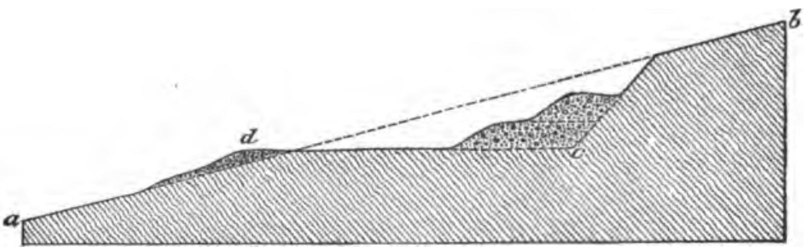


FIG. 47.—Profile of the Lithoid Terrace.

The line *a b* represents the original slope of the mountain side before it was modified by the waves of the lake. The Lithoid terrace *c d* was first formed, the outer edge being built of *detritus*. The magnitude and persistence of this terrace indicate that the water stood for a long time at a nearly constant level, allowing the waves to carve out a broad shelf from the solid rock. As we shall see farther on, the terrace became coated with calcareous tufa, and its gravel was cemented into a conglomerate. At some later period in the history of the lake the water rose and built the two small embankments or terraces that rest upon it, but it remained at those horizons only a comparatively short time.

The Thinolite terrace, 100 feet above the present level of Pyramid

Lake, can be followed all about the shore of that lake and about Winnemucca Lake, and appears again on the borders of the Carson Desert. This evidently marks the outline of Lahontan when its waters were greatly reduced by evaporation. As we shall find when examining the tufa deposits, the date of its formation is subsequent to that of the high, broad terrace just described.

Besides the terraces, there are bars and embankments of gravel, that are not only interesting as examples of wave action but also render much assistance in deciphering the history of the ancient lake.

At a locality about two miles west of Allen Spring, on the south side of the Carson Desert, there is a series of gravel embankments built one upon another and extending from the highest water line some distance down the mountain side. These structures were formed by currents from the westward bringing great quantities of gravel from a high sea cliff and depositing it in a series of embankments that are curved or hooked at the free extremity. A somewhat hasty examination of these gave the impression that they were built in ascending order, the lower ones being older than the upper, as though formed by the waves of a rising lake. The higher members of the series rest upon the broad, tufa-covered terrace thirty feet below the maximum water line, and prove by their position that they are records of a high water period subsequent to the first rise of the lake. This interesting group of embankments will be mapped and more fully studied during the coming field season, and will without doubt prove an instructive page of Lahontan history.

Another series of wave records, which for various reasons we regard as equivalent to the looped bars at Allen Spring, may be seen at the north end of Pyramid Lake. They consist of horizontal terraces built of rolled stones and masses of rounded tufa, and they cross the face of a steep bluff at nearly equal intervals from the highest water line down to the present water surface. They form a conspicuous topographic feature even at a distance of ten miles, and the marked contrast between the angular volcanic rocks above the ancient water line and the horizontal wave sculpture at the base of the cliff shows that the highest embankment of the series is the highest of all the shore records. We have christened the locality Terrace Point. As these terraces contain rolled fragments of tufa of a particular kind, their connection with Lahontan history cannot be fully set forth until the tufa deposits of the lake have been described. They will receive further consideration in another place.

At the southern end of Humboldt Lake a large gravel bar of Lahontan age sweeps in a gentle curve across the valley and forms a natural dam to confine the waters of the modern lake. This is a typical wave structure, constituted of well-worn gravel, and was built out from either shore until it was completed. It now stands like a huge railroad embankment, from fifty to sixty feet high, sweeping completely across the valley.

This bar received additions at various stages of the lake, and has a complicated structure. One of the latest events in its history occurred when the waters finally fell below its level. The body of water to the northward, receiving the tribute of Humboldt River, rose and overflowed across the lowest point of the bar and commenced the erosion of a channel, which was continued as the water of the main lake fell until the gravel dam was breached nearly to the bottom.

A barrier similar to the one which confines Humboldt Lake, but of greater height and with a more complicated history, was formed at the southern end of Winnemucca Lake, and at one time appears to have acted as a dam to the waters north of it. This structure, also, has been cut by drainage to its foundations.

A study of the bars fringing the ancient shores of Lahontan indicates that there were a number of periods of bar building; that is, separate dates when the lake was sufficiently deep, and remained long enough at one horizon, to allow its waters to construct heavy embankments of gravel.

CHEMICAL DEPOSITS.

An ordinary fresh-water lake, as is well known, is but the enlargement of a river, or else of several confluent rivers. To the geologist it is only a transient feature, for the time soon comes in its geological history when it is completely filled with sediment, being thus replaced by a plain through which the stream or streams meander. The water of such a lake has the normal composition of the streams that supply it, and remains fresh, for the reason that the mineral substances delivered to it in solution are discharged wite equal rapidity by the outflowing water. The solid substances, however, as sand and mud, which are carried into a lake by its tributaries, remain there; as is clearly seen when one contrasts the turbid and muddy waters of the inflowing streams with the free and pellucid waters that leave the lake to start afresh on their journey.

A lake without an outlet has a more complicated history than this, for it retains not only all of the solid substances delivered to it in suspension, but all of the material that the tributary waters have dissolved from the rocks with which they have come in contact. As the water of an inclosed lake escapes slowly by evaporation, leaving all dissolved mineral substances behind, the lake becomes more and more highly charged with various salts, until at length the point of saturation for some of them is reached and precipitation commences. Thus the density of lake water is frequently a rough index to the length of time that has elapsed since the formation of an inclosed basin, or since the date that the lake was last filled so full as to overflow and thus flood out the salts previously accumulated.

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[illegible] therefore [illegible]

[illegible] the [illegible]

[illegible] by [illegible] Forty-eight [illegible] Chemical Geology show [illegible] to 100,000 of water [illegible] Moreover, carbonate of [illegible] evaporation [illegible] precipitated. Con[illegible] of [illegible] deriving its supply [illegible] the United [illegible] by the [illegible] by precipitation from [illegible] was once reached [illegible] portion [illegible] for long periods. [illegible] and [illegible] As [illegible] upon another [illegible] is found in great abundance [illegible] on steep rocky slopes [illegible] by alkaline or lake [illegible]

[illegible]

[illegible] the rocky slopes of the [illegible] upward as far as any [illegible] could be [illegible] of the Carson Desert.

[illegible] p. 409.

[illegible] vol. I, p. 62.

Thinolite.

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Of lakes that do not overflow the examples best known are the Dead Sea and Great Salt Lake. The former contains from 21 to 28 per cent. of saline matter in solution, the amount varying in different places and at different depths. An analysis of the water of Great Salt Lake, collected in 1850, when the lake was unusually low and therefore much concentrated by evaporation, gave 22.282 per cent. of solid matter*; another analysis, from a sample collected in 1869, when the lake contained more water, gave 14.994 per cent.† Many of the lakes in the Great Basin contain large percentages of saline matter, but none so large as to rival Great Salt Lake.

The source of the saline matter held in solution by lakes without outlet is found in the inflowing streams. These, although fresh in the ordinary meaning of the word, are never absolutely pure, but on analysis show a small amount of mineral matter in solution. Forty-eight analyses of river water given by Bischof in his Chemical Geology show an average of 11 parts of carbonate of lime to 100,000 of water, and exhibit many other salts, but in less quantity. Moreover, carbonate of lime is a substance but sparingly soluble in water, and the amount actually contained by rivers frequently approximates the limit of saturation. When, therefore, a body of river water is concentrated by evaporation carbonate of lime is usually the first mineral to be precipitated. Considering that Lake Lahontan was a body of water deriving its supply from rivers, and that its basin exhibits a vast amount of calcareous tufa, restricted in its distribution to the limit marked out by the shores, the conclusion is inevitable that the tufa was produced by precipitation from the water of the lake. When the point of saturation was once reached and the deposition was initiated every additional portion brought by the tributary streams would produce an excess and lead to an additional precipitation. The deposition was thus continuous for long periods.

The basin exhibits three distinct deposits, each characterized by a separate variety of tufa. For convenience we shall designate these varieties, in the order of their age, *lithoid*, *thinolitic*, and *dendritic*. As the three deposits are superimposed one upon another their relative age is at once apparent. Each variety is found in great abundance, and they are especially well exposed on steep rocky shores and on outstanding buttes, where they could not be overplaced by alluvium or lake-beds.

LITHOID TUFA.

This, the first formed tufa deposit, is found on the rocky slopes of the basin from the level of the Lithoid terrace downward as far as any sections are now exposed. Its upper limit, wherever it could be determined, is the outer edge of the Lithoid terrace. It is well exhibited on the steep bluffs of basalt on the southern border of the Carson Desert

* Stansbury's Expedition to the Great Salt Lake, p. 419.

† Geological Exploration of the Fortieth Parallel, vol. I, p. 502.

and on the equally rugged limestone bluffs, known as Marble Buttes, at the south end of Pyramid Lake.

About one mile west of Allen Spring a small conical butte rises nearly to the level of the Lithoid terrace near at hand. Owing to its isolated position it could not be covered by shore drift, and it also escaped erosion to a great extent, so that it now remains almost completely sheathed with compact, gray, lithoid tufa. Here, as at many other localities, the deposit appears to consist of imbricated masses thatching the tops and sides of the butte. Or one can imagine it had been poured upon the butte from above and congealed as it flowed down the sides. This latter semblance, however, is due in great measure to weathering.

Near its upper limit this tufa is seldom more than a few inches thick, at least as it remains at the present time, but it increases as we follow it down the slopes. In many places it forms a cement for the gravel embankments and for the material constituting the surface of the Lahontan alluvial slopes. On the butte near Allen Spring, as well as at many other localities, and especially at the southern end of Pyramid Lake, its sheet shows many horizontal lines or bands, where it has been more or less completely removed by shore action, thus recording fluctuations of lake level subsequent to its deposition. In other places, where the shore is less steep, the tufa has been completely removed, or else buried beneath shore drift. At a number of localities the shells of fresh water gasteropods have been found in great abundance imbedded in the solid tufa, thus indicating that the lake when it first rose consisted of fresh water. As compared with the other varieties, this first formed tufa is usually gray in color and compact in structure. It sometimes shows irregular concentric bands and open spaces, but is far more dense and stone-like than the varieties subsequently deposited. Between its layer and the one that was formed over it we sometimes find layers of cemented sand and gravel. The surface of the lithoid tufa also shows the effects of a weathering before it was covered by the second deposit. From this we learn that the surface of the lake fell in the interspace between the deposition of the first and second tufas. How nearly it approached complete desiccation we are unable to state, but it certainly reached a lower level than the present surface of Pyramid Lake.

THINOLITIC TUFA.

The second layer of tufa was deposited at a lower water stage than the first, and is of a very different nature. The upper limit of its deposit on the sides of the basin is the Thinolite terrace, 100 feet above the present (1881) level of Pyramid Lake. Its geographic extent is shown on the accompanying map. It occurs about Pyramid and Winnemucca lakes and at a few localities on the borders of the Carson Desert. These two areas were possibly connected, at the time the thinolitic tufa was formed, by a strait extending through the cañon north of Wadsworth, as indicated

on the map. This valley or cañon is now occupied by the lower portion of the Truckee River, and has been deeply filled with gravel and lake-beds, whose relation to the thinolitic tufa it is difficult to determine.

The external character of this tufa is shown in the right-hand upper figure of Plate XXV in Volume I of the Fortieth Parallel Survey. It is the variety that led Mr. King to give the name "thinolite" to the tufa deposits throughout the Lahontan Basin. But since we have been able to discriminate three distinct deposits, and since only one of these exhibits the characters described by Mr. King, we have preferred to restrict the name to this second deposit and apply other titles to the overlying and underlying layers.

The thinolite differs from the other tufa of the basin, and from calcareous tufa in general, in that it is constituted of crystals. These crystals are orthorhombic prisms, with faces and angles somewhat obscure and rough, and without well-defined terminations. They are often 6 or 8 inches in length, with a thickness of half an inch. They are light gray in color, and are seldom solid throughout, but contain flattish cavities more or less parallel with their sides. Weathered specimens frequently exhibit an imbricated structure, as if formed of thin pyramids or hoppers set one within another. The edges of these hoppers when broken across appear as lines parallel with the sides of the prisms. These crystals are announced in the Reports of the Fortieth Parallel Survey as pseudomorphs after gaylussite, and as they are intimately connected with the chemical history of Lake Lahontan they will necessarily receive great attention as the study of that history is pursued. It is interesting in this connection to note that identical crystals were also formed on a large scale in the Quaternary lake that occupied Mono Valley, California.

Where best exposed the layer of interlaced crystals has a thickness of from 6 to 8 feet, and exhibits concentric zones of larger and smaller crystals. (See Plate XIX.)

DENDRITIC TUFA.

We have given this name to the third variety of tufa—that deposited after the formation of the thinolitic crystals. This is the most abundant of the chemically formed rocks in the Lahontan Basin, and in places attains a great thickness. Its greatest depth is not less than 20 feet and may be as much as 50. The upper limit of the deposit is not definitely determined, but is about 200 feet below the highest water line, and from this level downward it coats the sides of the basin wherever the conditions are favorable. Like the previously formed varieties it was deposited on rocky slopes and outstanding buttes, where the action of the shore drift was least and where a solid nucleus could be found for the commencement of crystallization. The finest displays examined by the writer are to be seen on the high rocky buttes, once a Lahontan island, that rise just south of Carson Lake, and on the steep rocky shores

[illegible] larger [illegible] flake [illegible] Feldspar [illegible] Mr. King [illegible] preferred [illegible]

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[illegible]

[illegible] the tradition [illegible] [illegible] ends [illegible] would [illegible]

Dendritic Tufa.

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of Pyramid and Winnemucca lakes. The islands in Pyramid Lake are thickly coated.

Dendritic tufa occurs also over large portions of the bottom of the old lake, especially on the surface of the plain through which the Truckee River has cut a recent channel between Wadsworth and Pyramid Lake. In this region it is found in dome-shaped bodies, starting from small nuclei and spreading out to form mushroom-shaped masses of all sizes up to 5 or 6 feet in diameter. These completely cover the surface of the lake-beds over an area several square miles in extent. Another fine locality for tufa domes of this nature is on the surface of lake-beds in the cañon of the Carson River about 20 miles west of Ragtown. The mushroom-shaped masses occur here in great profusion, and are commonly polygonal in outline, owing to their having interfered with each other's growth. In places they are hexagonal and form a complete pavement on the surface of the lake-beds, each block being about 2 feet in diameter. Not infrequently one of these mushroom-shaped masses has weathered away at the top so as to form a vase-shaped cup that exhibits within the dendritic structure of the tufa—branching twigs of stone radiating on all sides from the small nucleus about which they first commenced to crystallize. This structure is shown in the accompanying plate, which represents a section of a dome after the top, to the depth perhaps of a foot, had been removed by weathering.

The dendritic tufa sheathing the steep cliffs exhibits similar mushroom forms, but far less perfect than those growing from isolated nuclei on the surface of the desert. The swelling bosses of tufa that cover the rocks in imbricated masses are usually weathered at top into shallow cups, and these have often a striking resemblance to swallows' nests coating the face of the cliff. The characteristic dendritic structure of this variety of tufa, exhibited in the plate, is so pronounced that even small weathered fragments can be identified with certainty. The appearance of the Lahontan shores when coated with this tufa is well shown in Plate XXIV of Volume I of the Reports of the Fortieth Parallel, and also in Plates XXI and XXII of this volume.

SUCCESSION OF TUFA DEPOSITS.

The accompanying diagram, Fig. 48, gives a generalized expression of the relation of the three successive tufas to each other and to the sides of the basin. The first formed deposit, the lithoid tufa, represented in the notation of the diagram by vertical lines, extends upward about 500 feet above the horizontal lake-beds occupying the bottom of the basin. The second deposit, the thinolitic tufa, finds its upper limit 100 feet above the present level of Pyramid Lake. The third and last, the dendritic tufa, which is far more abundant than either of the oth-

ers, extends upward to within about 200 feet of the highest shore line. The lower limits of these deposits cannot be determined with certainty, as they are concealed by lake-beds.

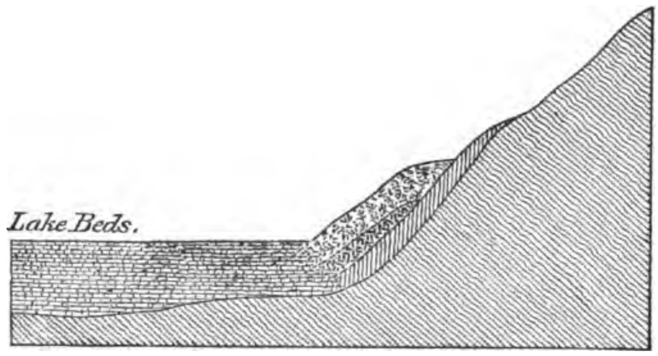

FIG. 48.—Diagrammatic section illustrating the Relations of the Tufas.

Chemical analyses were made by Prof. O. D. Allen of samples of each of these varieties of tufa, and the results, given below, show that their constituents are practically identical. The insoluble residue exhibited in each case may be due in part to foreign matter imprisoned in the tufa at the time of its formation, and is certainly due in a measure to foreign matter carried by atmospheric agencies into open cavities of the rock after the desiccation of the lake.

	Lithoid tufa.	Thinolitic tufa.	Dendritic tufa.
Insoluble residue	1.70	3.88	5.06
Lime (CaO)	50.48	50.45	49.14
Magnesia (MgO)	2.88	1.37	1.99
Oxide of iron and alumina	.25	.71	1.29
Carbonic acid (CO_2)	41.85	40.90	40.31
Water (H_2O)	2.07	1.50	2.01
Phosphoric acid (PO_5)	.30	Trace.	Trace.
Chlorine and sulphuric acid	Trace.	Trace.	Trace.
	99.53	98.81	99.80

Not only do these tufa deposits still sheathe the slopes of the Lahontan Basin, but they appear also in isolated, castellated masses and rugged crags about the shores of Pyramid and Winnemucca lakes and on the borders of the Carson Desert. These outstanding masses occur characteristically as upright cylinders, or groups of cylinders, with rounded, dome-shaped tops, and are of all sizes, from a few inches up to a hundred feet or more in height. The larger masses are composed of groups of many tower-like, cylindric bodies of unequal height, and bear a striking resemblance to rugged mediæval castles with rounded towers and

castellated battlements. A fine example of such a water-built castle stands about the middle of the western shore of Pyramid Lake, and rises 100 feet above the waves that wash its base. The domes between the eastern shore of the lake and Pyramid Island are the tops of similar towers, the foundations of which are deeply submerged. Other masses of the same nature, but smaller in size and usually broken and weathered, occur in abundance. Frequently these outstanding cylinders and castles of tufa are broken across, or split from base to summit, so as to reveal every desired section of their interiors. An examination of a large number of these dissected masses brought to light the interesting fact that all the tufa crags below the broad terrace 100 feet above Pyramid Lake—the Thinolite terrace—have a tripartite structure, and all above that horizon have a bipartite structure.

Each of the tufa towers below the Thinolite terrace has a core of compact gray tufa in all respects identical with the first-formed sheath of tufa on the rocky sides of the basin. This core of lithoid tufa is commonly from 2 to 6 feet in diameter, and sometimes shows a tubular structure. When the base is exposed it is occasionally seen to spring from a small nucleus of rock.

Outside the core of gray tufa is a coating of thinolite crystals, from 2 to 6 or 8 feet thick, that completely envelops its sides and top. These crystals are interlaced in every direction, but show a radial grouping, and also a concentric banded structure—zones of elongated prisms alternating with narrow bands of smaller crystals. The largest crystals are from 6 to 10 inches in length and an inch or more in diameter. This layer of thinolite is best displayed in the masses of tufa that occur low down near the surface of Pyramid Lake. The deposit is there thickest and the crystals are largest.

About the layer of thinolite, and in turn completely covering it, is a third tufa deposit, equal to or even exceeding in thickness either of the previous layers. It usually arches over the top of the column in a low dome. This third layer is of dendritic tufa and always shows the characteristic branching structure, resembling a group of cedar boughs changed to stone.

Frequently the dome-shaped summits of these tufa towers are weathered into holes, and sometimes the entire top is dissolved away down to the layer of thinolite crystals, or even deeper. In the hollows thus formed, which are frequently 10 or 12 feet in diameter, a person can stand as on the top of a wide tower, with a parapet of dendritic tufa 3 or 4 feet high all about him. On the west side of Winnemucca Lake, near the southern end, there stands a tufa tower, fully 40 feet high, that has been split from base to summit into three sections, the open fractures being wide enough for a person to pass through. In remembrance of Heidelberg I have called this the "Rent Tower." The whole of this tower is composed of tufa, the nucleus from which it

started being some distance below the surface of the surrounding lake-beds and gravels. It stands just above the level of the Thinolite terrace and is composed entirely of lithoid and dendritic tufa, the middle or thinolitic member being wanting. Near at hand and a few feet below the horizon of the Thinolite terrace are other dome-shaped masses showing the intermediate thinolite also.

While the isolated tufa towers having thinolite as a middle member are confined to the shores of Pyramid and Winnemucca lakes and to the borders of the Carson Desert, the similar masses in which the thinolite is wanting occur over a much wider area, especially along the borders of the Black Rock Desert. Examples may also be seen along the line of the Central Pacific Railroad southeast of Humboldt Lake.

In some cases where the lake-beds and gravel have been washed away from the base of a tufa tower, we find the outer layer of dendritic tufa projecting as an irregular shoulder about the lower part of the column, thus showing how much of the column projected above the bottom of the lake at the time the dendritic layer was added. In one instance, where the entire mass has been uprooted, the layer of thinolitic crystals extends about 2 feet lower down than the coating of dendritic tufa, and then terminates in the same abrupt manner. In this case the central core of lithoid tufa ends in a tapering, irregular base, the nucleus of which is a group of small pebbles.

One of the physical conditions favorable, if not absolutely necessary, for the formation of tufa seems to be the presence of a solid nucleus about which the carbonate of lime can commence to crystallize. This nucleus may be a pebble resting at the bottom of the lake or it may be the solid cliff that forms the shore. It plays the same role here as it does in the crystallization of alum or rock candy in a laboratory experiment, or as may be seen in the structure of oolitic sand. The crystallization once started, the process was continued until hundreds and even thousands of tons had formed in a single isolated mass. Where the shores are too steep and solid for the ready formation of terraces and embankments of gravel they favor the deposition of tufa. In such places the chemical deposit cannot be disturbed or carried away by the shore drift. The most favorable places of all for the accumulation of calcareous deposits are rocky islands. Tufa frequently cements the gravel and sand of which embankments are constructed, and sometimes forms a complete pavement on their surfaces. This happens when by a rise of the lake the surface of the embankment is so far submerged as to escape the action of the shore drift. Tufa has never been observed by the writer resting on beds of fine clay or silt unless there were pebbles for nuclei. In many instances every pebble on a surface of fine lake-beds has its upper surface coated with tufa, or perhaps supports a mushroom-shaped growth some inches in height, while the surrounding plain of fine mud is entirely free from calcareous deposit.

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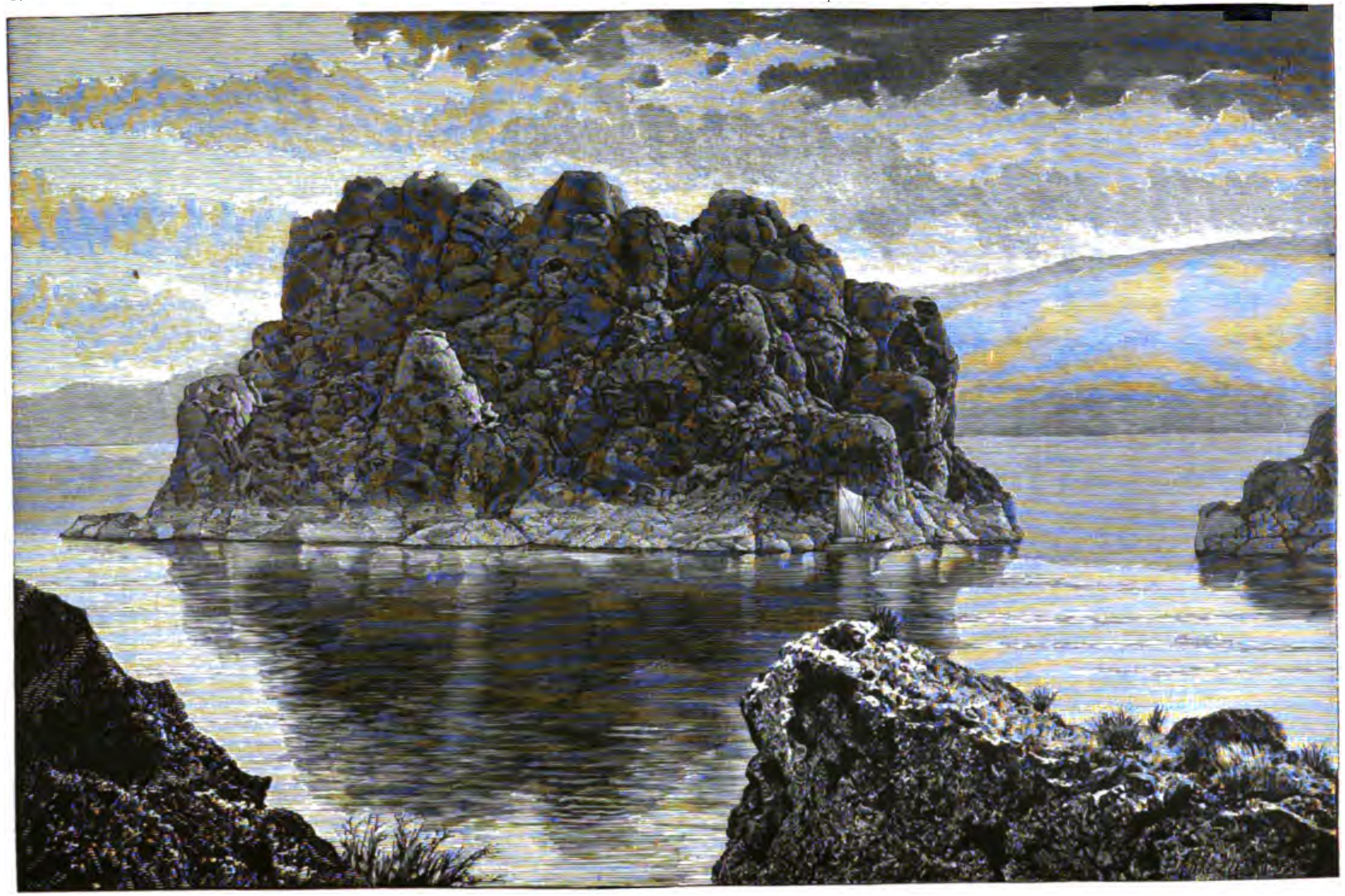

TUFA DOMES—SHORE OF PYRAMID LAKE.

It has been suggested that these isolated tufa masses may have been formed by springs rising in the bottom of Lake Lahontan. That this is not the explanation of the origin of all the structures is shown by the frequently observed presence of a nucleus; the structure of the different varieties of tufa; their occurrence on rocky slopes; the correspondence of the three members composing the isolated masses below the Thinolite terrace with the three coatings of tufa sheathing the interior of the basin below that terrace; and the further correspondence of the two members composing the masses above the Thinolite terrace with the two coatings of tufa sheathing the rocky slopes above that terrace. The mounds of calcareous tufa deposited about hot springs have a structure, at least when formed on land, like that represented in cross section by the diagram, Fig. 49. If the spring has a single orifice the tufa is de-deposited on both the inner and outer edges of the rim in irregular, imbricated layers that build up a more or less perfect cone about it. Such a cone is broad in proportion to its height, and is irregular in structure.

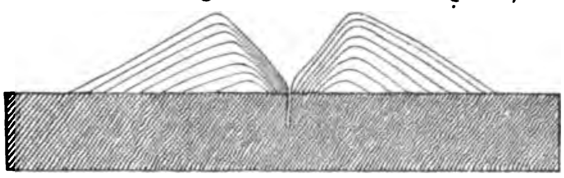

FIG. 49.—Ideal section of a Spring Deposit.

In the tufa domes of Lake Lahontan the height is usually much greater than the diameter, and the structure is always exogenous, as indicated in Fig. 50, which is a rude representation of a section of one of these domes observed near the shore of Pyramid Lake.

On the other hand, the tubular structure of the inner core of lithoid tufa—in some instances branching irregularly and spreading out as it rises—certainly indicates that the formation of some of the isolated domes or crags has been initiated by the action of subaqueous springs. The deposition of carbonate of lime from springs rising under water has not been observed in any of the present lakes of the Lahontan Basin. It is possible, however, that the waters of these lakes are not sufficiently charged with mineral substances to cause the springs to deposit their lime when they come in contact with it. In Mono Lake, where the waters are strongly alkaline and saline, there are a large number of sub-lacustrine springs that are now depositing carbonate of lime and building tufa towers. In many instances these deposits are formed of porous and tubular tufa, closely resembling some of the lithoid tufa that forms the cores of the towers about Pyramid Lake.

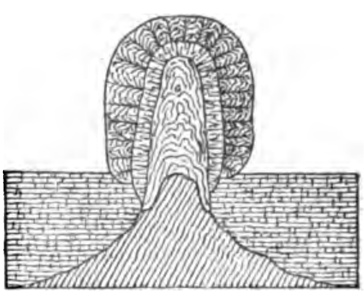

FIG. 50.—Generalized section of Tufa Dome.

It is evident, then, that the formation of isolated tufa towers commences in two ways. In some instances the carbonate of lime begins

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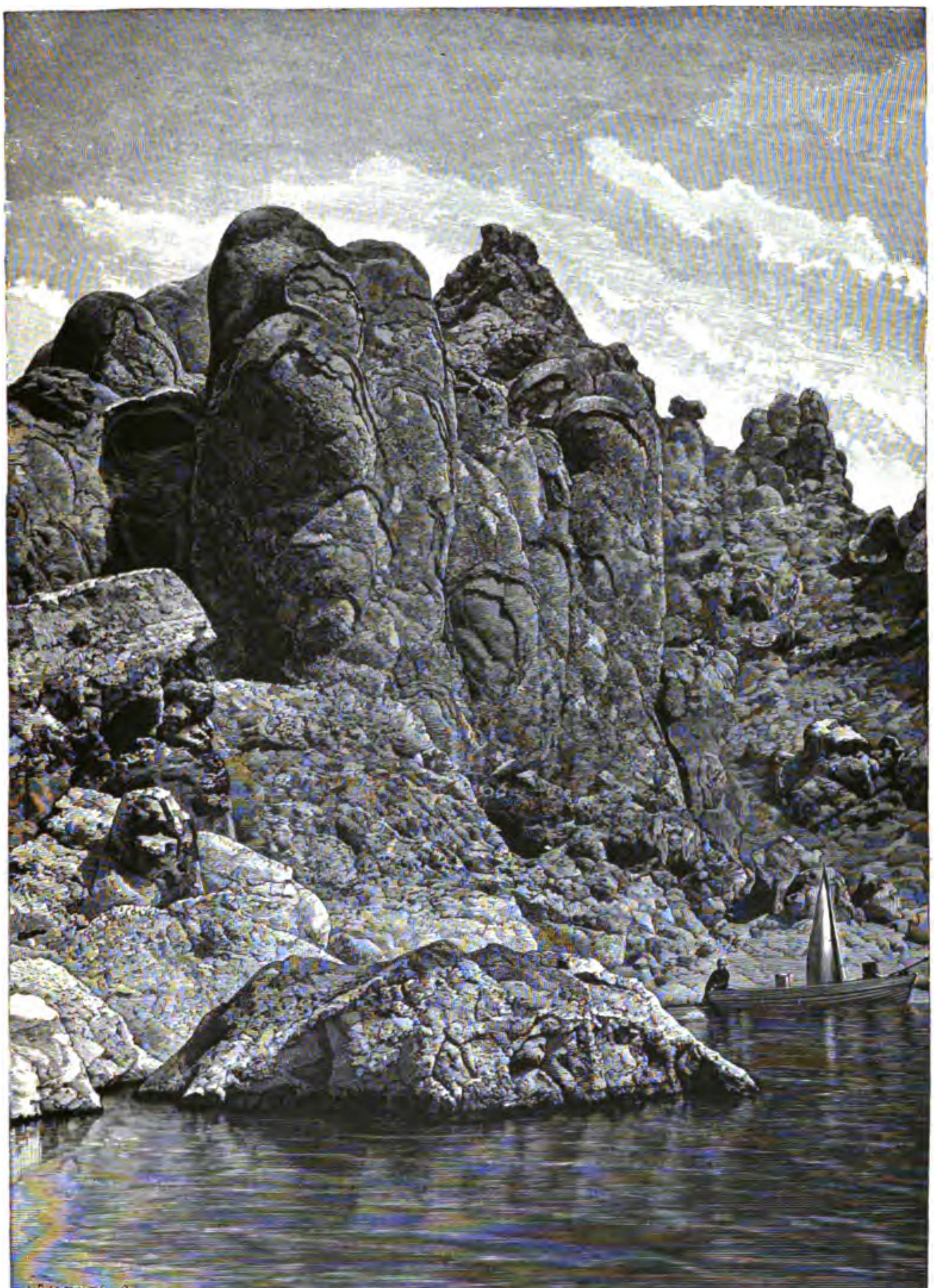


TUFA DOMES—SHORE OF PYRAMID LAKE.

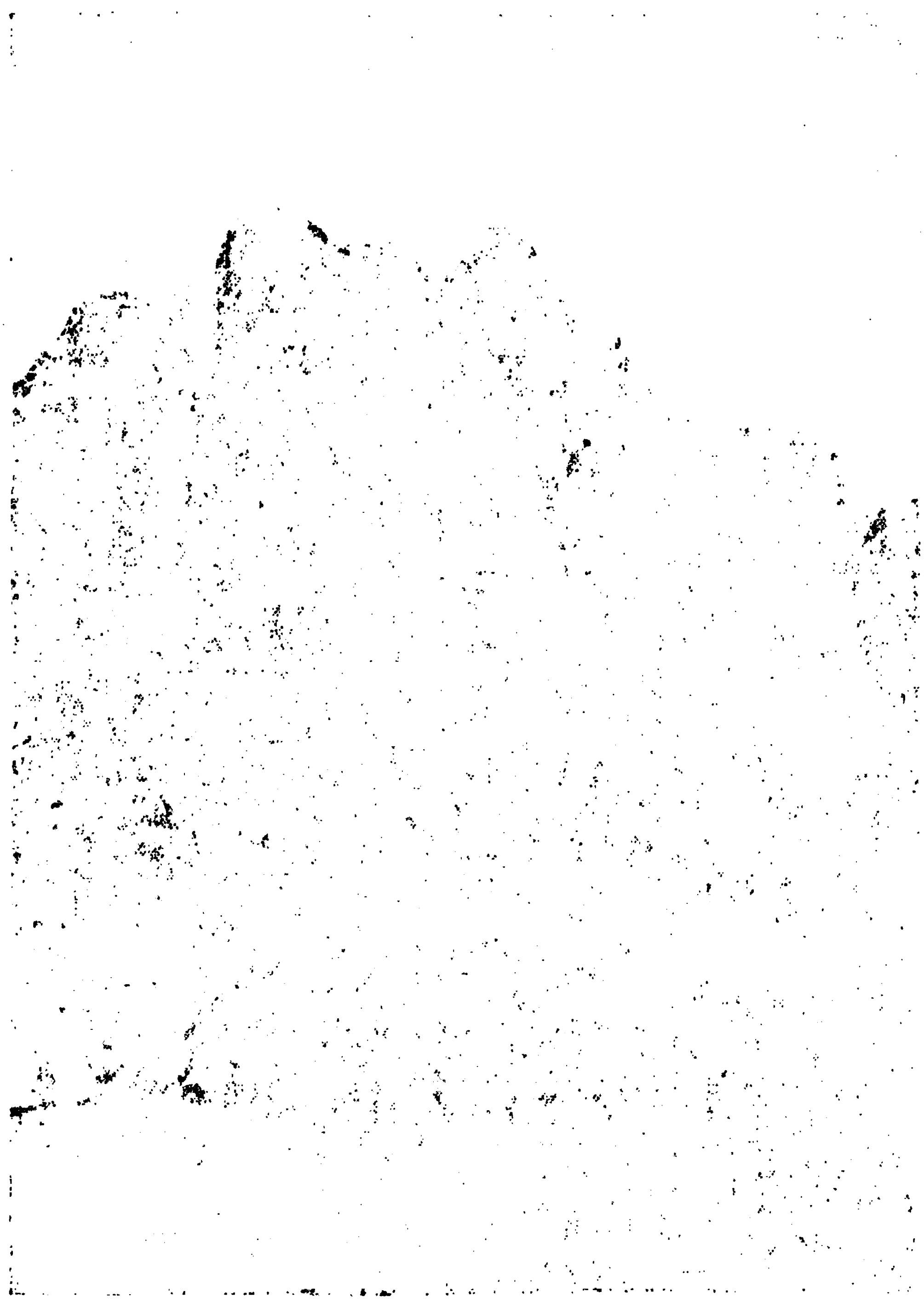
to crystallize about a solid nucleus; in others the beginning is made by a deposition from springs that rise in lakes already highly charged with mineral salts. In the case of the towers about Pyramid and Winnemucca lakes, which have a core of tubular lithoid tufa completely enveloped by subsequently formed layers of the thinolitic and dendritic varieties, we must conclude that the lithoid tufa owes its formation to the action of submerged springs, while the outer layers were precipitated directly from the waters of the lake.

As the different varieties of tufa were deposited at separate periods, we should expect to find, in favorable localities, a succession of lake-beds or gravel deposits with intervening layers of tufa. This is also suggested by the unequal distances to which the different layers of tufa extend downward on the sides of the tufa domes. In our search for exposures of this nature we were only partially successful. In the sides of a deep cañon the Truckee River has excavated through Lahontan beds near its entrance into Pyramid Lake we found a layer of dendritic tufa, from 4 inches to 2 feet thick, exposed for some miles along the walls of the cañon, with well stratified lake-beds both above and below. A similar exposure has also been observed at Mill City, where the Humboldt River has excavated a deep channel through Lahontan sediments. No interstratification of thinolitic or lithoid tufa with beds of sedimentation has yet been observed.

We learn from the tufa deposits that there have been at least three well-defined periods in the history of Lake Lahontan. When the first tufa was formed the lake filled its basin to within 30 feet of the highest water line now scoring its sides. This tufa contains the shells of fresh-water gasteropods, showing that the lake was then fresh.

At a later date, when the volume of water was much less and the surface of the lake marked a shore line 400 feet below its former level, the broad Thinolite terrace was carved, and the chief deposit of thinolite crystals was formed. If the thinolite is a pseudomorph after gaylussite, then we can safely say that the waters of Lahontan were highly charged with soda and must have had a chemical composition resembling that of the waters of the Ragtown Ponds, in the Carson Desert, where beautiful crystals of gaylussite are now forming. At present we are unable to determine at what date after the formation of the gaylussite crystals the pseudomorphism took place, or what became of the soda once contained in the gaylussite and now replaced by lime. As Lake Lahontan never overflowed, the escape of this immense amount of soda from the basin is impossible. The question thus arising is one of the most interesting subjects for future investigation in connection with the history of the lake.

In the epoch of the dendritic tufa the water rose 200 or 250 feet above the Thinolite terrace, and the heaviest of all the tufa deposits was precipitated. No broad and well-defined terrace marks the upper limit of



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[illegible] the water rose 260 or 270 feet above [illegible] the heaviest of all the tufa deposits was [illegible] defined terrace marks the upper limit of

TUFA DOMES—SHORE OF PYRAMID LAKE.

this deposit, and it is probable that the lake underwent many fluctuations of level during its formation. We find fragments of dendritic tufa built into the embankments that were formed at a later date, and also lake-beds resting on its layers. The final rise of the lake recorded by these phenomena was the highest rise of all. In the lagoons confined by the last formed bars we find gasteropod shells in abundance, and in the contemporaneous lake-beds resting on the dendritic tufa are hundreds of shells of *Anodonta*, indicating that the lake was fresh at this period.

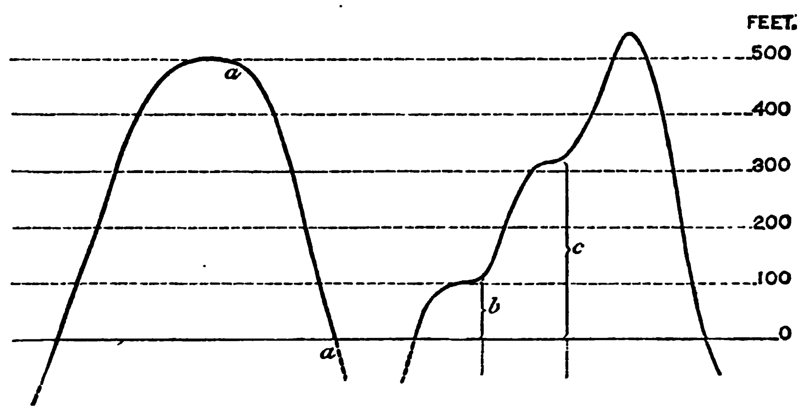


FIG. 51.—Curve exhibiting the Rise and Fall of Lake Lahontan; *a a*, deposition of lithoid tufa; *b*, deposition of thinolitic tufa; *c*, deposition of dendritic tufa. The zero of heights is the level of Pyramid Lake.

If we project the fluctuations of Lake Lahontan in a curve (Fig. 51), the ordinates representing depths of the lake at various stages, and the abscissas succession in time, we find there are two maxima and two minima. We have two moist periods when the lake was deep, separated by a time of desiccation, and followed by the present period of aridity. We know that the first of the two high water periods was the longer continued, for the terraces the waves then cut in the rocks are broader and more strongly marked than the terraces recording the second rise. The second high water period was of short duration, but the lake rose to a higher level than at the first filling.

SEDIMENTARY DEPOSITS.

The various streams which entered Lake Lahontan deposited at their mouths a large portion of the material brought down in suspension and formed delta accumulations. Owing to the many fluctuations of the lake level, however, these deposits have been mostly destroyed, or have been so modified and buried beneath lake gravels and lake-beds that no well-defined deltas now remain. The splendid preservation of

the deltas of Lake Bonneville, as compared with those of Lake Lahontan, appears to be due to the fact that they were built at horizons determined by overflow, and were never afterward submerged or brought within the action of shore currents.

The rivers that entered Lake Lahontan fell at moderately low grades, and consequently carried mostly finely comminuted sediments and well-worn gravel. When they reached the lake the gravel and coarser material were deposited, while the impalpable mud was carried far out from shore and served to form lake-beds. The suspended material brought down by the Humboldt River was deposited largely in the long, narrow arm extending from the river mouth in the Sonoma Range to the present Humboldt Lake. These beds now form the nearly level floor of the valley, and may be seen in section in the sides of the deep cañon recently carved by the Humboldt River. The beds thus exposed are variable in composition, and seldom show identical sections at points half a mile apart. At many localities, as for example at Mill City, they are grouped in three divisions, thus:

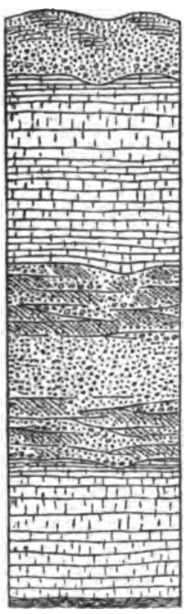


Fig. 52.—Section of Quaternary strata at Mill City, Nevada.

Lake-beds. Fine, evenly stratified, drab clays, weathering into cubical blocks, and containing *Anodonta;* partly covered by Æolian sand.................. 10 to 20 feet.

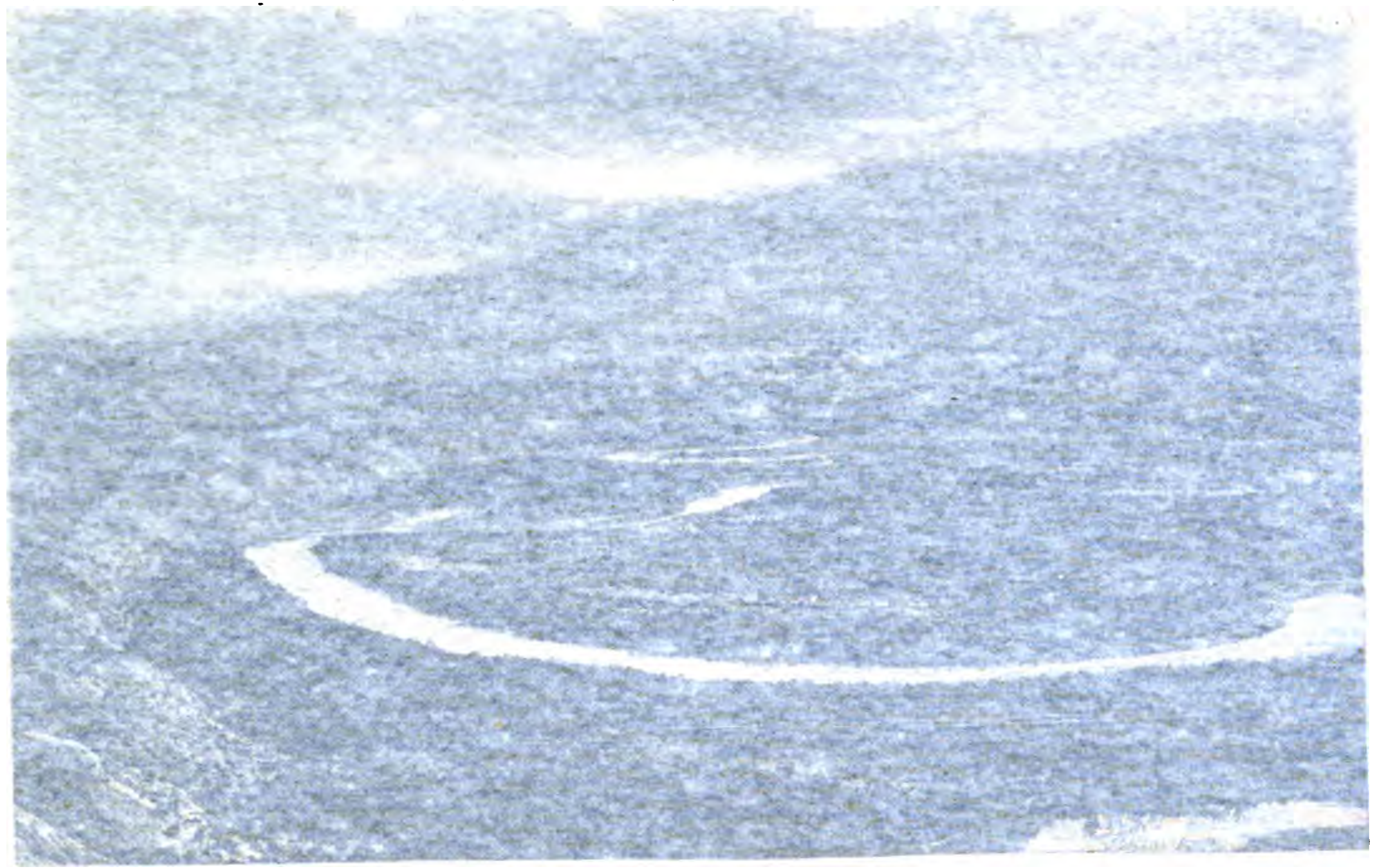
Layer of *Dendritic Tufa.*

River gravels. Cross-stratified sand and gravel, with *Limnæa,* etc.......................... 12 to 18 feet.

Lake-beds. Fine, evenly stratified, drab clays.................... 8 to 12 feet.

This sequence of strata gives evidence of two periods when lake sediments were deposited in quiet waters, separated by a low-water period, when stream-borne, current-bedded gravels were spread out over the lower lake-beds. The middle member of the section is unconformable with the beds of clay, both below and above it, as indicated in the diagram.

This section, with various modifications of its middle member, may be followed for some miles along the cañon walls of the Humboldt, in the



LAHONTAN LAKE-RIDGES IN HUMBOLDT VALLEY.

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[illegible], Cross-stratified sand [illegible], with *Limnaea*, etc. ... [illegible]

[illegible] Fine, evenly stratified, [illegible] ... 8 to 12 feet.

[illegible] sequence of strata gives evidence of two [illegible] when lake sediments were deposited [illegible] a low-water period, when stream borne [illegible] spread out over the lower lake beds. The [illegible] section is unconformable with the beds of [illegible], as indicated in the diagram.

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LAHONTAN LAKE-BEDS IN HUMBOLDT VALLEY.

neighborhood of Winnemucca and Mill City. The shells found abundantly in the gravels have not yet been determined specifically, but they are identical with those occurring in the Lahontan tufas, and would point to the identity in age of these deposits, even if other evidence were lacking.

As we follow southward the section of lake-beds exposed by the Humboldt we find them more and more marly, with less and less gravel, until finally it is difficult to determine with accuracy the three members so conspicuous at Mill City. The cañon walls near Rye Patch are fully 200 feet high, and are cut by side drainage into typical bad-land forms, as illustrated by Plate XXIII.

At the highest stage of Lahontan the water extended up the cañon of the Truckee River to a point 15 miles west of Wadsworth. While it stood there it checked the flow of the water, and received from the river only fine material; but when the lake afterward fell, the grade of the stream was increased, and coarse material was carried out over the lake-beds. Still later, when the waters of the lake finally subsided, the *débris* that filled the cañon west of Wadsworth was mostly removed by the river, and at present only fragments of the lake-beds remain clinging to the sides of the cañon in sheltered places.

During the final desiccation there must have been a time when the Truckee flowed out over the nearly horizontal lake-beds filling the narrow strait about Wadsworth, and was free to turn either to the north or to the south. Without any apparent reason for the choice it turned northward, and it has cut a deep cañon through delta material and lake-beds to the depressed area now occupied by Pyramid Lake. The sections displayed by the vertical walls of this cañon show many variations, just as in the Humboldt River sections, but in many places there are two deposits of lacustrine clays, separated by a broad band of current-bedded gravel. Here also we find, as shown below, a continuous stratum of dendritic tufa, with evenly-bedded, fine-grained lake-beds both above and below it.

GENERALIZED SECTION ON EAST BANK OF TRUCKEE RIVER TWO MILES ABOVE THE INDIAN AGENCY.

	Feet.	
Æolian sands	0 to 20	
Fine yellow sands in contorted strata	20	Lake-beds.
Evenly stratified, drab clays, jointed	4	
Dendritic tufa	0.3 to 2	
Evenly stratified, drab clays, jointed	12	
Current-bedded gravels and sand in irregular strata, with partings of clay.	80	Shallow water deposits.
Evenly stratified clays, to river	20	Lake-beds.

In the cañon of Carson River the history given by the Humboldt and Truckee rivers is again repeated. This was a deeply eroded cañon before the formation of Lake Lahontan. The lake occupied it as far up as Dayton, and below that point the sediments brought by the river were deposited, partially filling the ancient valley. When the lake receded

the river flowed over the soft lake-beds and cut them away, forming a cañon within an older cañon, the older and larger cañon being carved out of solid volcanic rock, and the newer one eroded from soft lake-beds, as indicated in the diagram.

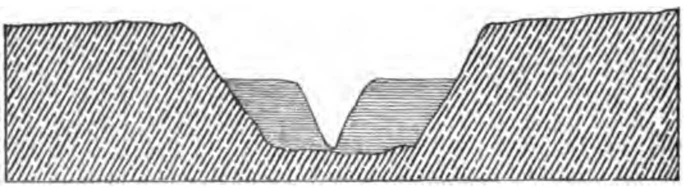

FIG. 53.—Ideal section illustrating the relation of the Ancient and Modern Cañons of Carson River.

In the cañon of Walker River, between Mason Valley and Walker Lake, these conditions are again shown.

In each of these cases the delta accumulations and lake-beds filling the old cañon extend up the river to a point where the contour marked by the horizon of the former lake crosses the valley. In each case, also, the strata contain fossil shells that are identical with those found in the tufa deposits of the old lake.

All the deposits occurring near the mouths of the tributaries of Lake Lahontan are similar in general character, varying from fine drab clays and white marls to coarse gravel. At a distance from the Lahontan shores, however, and forming the level floors of the broad deserts, are sediments of a different character. Over the most of the Carson and Black Rock deserts the material, to a considerable depth at least, is of fine, greenish, tenacious clay, having a remarkably uniform appearance over wide areas. This sediment, being deposited far from the mouths of the rivers, could only be formed of the finest silt, such as might be transported long distances and at the same time resist the solvent action of the water. It is composed mainly of the silicate of alumina, but contains also some soluble salts that appear to have been absorbed from the brine of the lake as the latter was evaporated to dryness.

DESICCATION PRODUCTS.

If Lake Lahontan had overflowed, the most of the salts carried into it by tributary streams would have been flooded out, but as it never found outlet it is evident that all the material delivered to it in solution must still remain in the basin. It is to the saline deposits left by the evaporation of the ancient lake that the term "desiccation products" is applied.

The study of the saline residua of the fossil lakes of the Great Basin

is perhaps the most puzzling of the problems they present, the difficulty in arriving at the facts being due to the burial of the precipitated salts beneath the level and unbroken surfaces of the deserts, and also to the changes the chemical compounds have undergone since their first deposition.

A lake which disappears by evaporation may leave a stratum of salt upon its bed, as in the case of Sevier Lake, Utah, and the lake which once occupied Osobb Valley, Nevada. In each of these instances the bed of the extinct lake is now a dazzling field of salt many square miles in area. In other cases lakes have evaporated to dryness without leaving a layer of salt, but have left the lacustrine beds beneath saturated with a strong brine. An instance may be seen in Diamond Valley, Nevada, and there are a number of others in dry valleys of the Great Basin where playas occupy the sites of ancient lakes. The North Carson Lake, otherwise known as the Carson and Humboldt Sink, affords an example of the evaporation of a large lake of alkaline and somewhat saline water without the formation of a field of salt. It is a shallow lake, and has usually a length of more than 20 miles and a breadth of 12 miles, but in consequence of a series of unusually dry seasons it has been known to disappear by evaporation, leaving a plain of saline mud. Over the surface of this mud there is a profuse efflorescence of salt, testifying to the presence of that mineral in large quantities in the lake-beds beneath.

In the Lahontan Basin the salt once held in solution by the water nowhere exists as a surface deposit, but impregnates, or else is buried beneath, the fine clay sediments with which the plain is floored.

The presence of saline substances whitening the surface of the deserts during the drier portions of the year is due to the formation of a crust by efflorescence and not to the precipitation of salt on the evaporation of a lake. Areas many miles in extent are thus covered with impure layers of various salts, varying from a fraction of an inch up to five or six inches in thickness, the soluble minerals which impregnate the clays beneath being brought to the surface in solution by capillary action and there deposited as the water is evaporated. These incrustations are usually composed chiefly of the chloride of sodium and the sulphate of soda, with smaller quantities of carbonate and borate of soda, and with still smaller percentages of the sulphates of calcium and magnesium.

The best idea of the nature of the salts impregnating the Lahontan sediments can be obtained by an examination of the various salt works located within the lake basin.

BUFFALO SALT WORKS.

At the Buffalo Salt Works, situated on the west side of Smoky Creek Desert, the brine from beneath the desert is allowed to collect in wells, and is then pumped into vats at the surface and left to evaporate. The crust of salt that remains is then gathered, and is found sufficiently pure

for all domestic uses. About 250 tons are annually collected, the total amount produced since the works were started being not far from 1,500 tons. When fresh water is caused to flow over the surface of lake-beds in the vicinity it soon becomes strongly saline, and when it gathers in hollows and evaporates it leaves a crust of salt that is sometimes several inches in thickness. This method is employed to some extent for obtaining the less pure grades used principally for chloridizing silver ores.

Two miles east of the works there are level, pond-like areas on the surface of the desert that are usually covered with a white efflorescence some inches in thickness. Other depressions are soft and completely saturated with bitter brine. In some there are deposits of sulphate of soda at least several feet in thickness, but never probed to the bottom. When examined by the writer these sulphate beds were covered to the depth of several inches with mother-liquor or soft mud that rendered the surface unsafe to walk upon. The whole desert region on the edge of which the Buffalo Salt Works are situated is one vast stretch of yellowish mud, without vegetation, impassable except during the dry season, and locally known as the "Mud Lakes." The salt obtained from the wells of the salt works, and the sulphate of soda and other minerals found on the surface near at hand, are all derived from the salts impregnating the Lahontan lake-beds.

The brine from the wells has been analyzed by Mr. F. W. Taylor, of the National Museum, with the following result:

Specific gravity, 1.1330.

Silica in solution	Trace.
Calcium sulphate	0.1467
Magnesium sulphate	.8833
Potassium sulphate	.3111
Sodium sulphate	.5306
Sodium chloride	14.8383
Water	83.2900
	100.0000

EAGLE SALT WORKS.

Another locality favorable for the study of the desiccation products of Lake Lahontan is at the Eagle Salt Works, situated near the Central Pacific Railroad, about 18 miles east of Wadsworth. The long valley in which they lie was a strait during the higher stage of Lake Lahontan. When the water fell about 100 feet the region where the salt is now found became a bay, connected with the Carson division of the lake through the Ragtown Pass. The country about the works is a desert mud plain, much of which is covered during the summer by a white saline efflorescence. The method here employed for obtaining the salt is to dissolve the crust that is formed on the surface of the desert and allow the saturated water to gather in shallow vats and evaporate. The water from springs on the eastern edge of the plain is conducted over the surface of the lake-beds, and made to flood small

areas inclosed by low dams or ridges of clay. From the flooded areas it soaks through the clay ridges and enters shallow vats dug in the lake-beds on either side, where it evaporates and deposits its salts. The areas inclosed by clay ridges and flooded by the fresh water are called "reservoirs" by the workmen, and the long troughs between them where the brine evaporates are known as "vats." These are arranged alternately and may be multiplied to any extent. A profile through a reservoir and the vats on either hand is shown in the diagram.

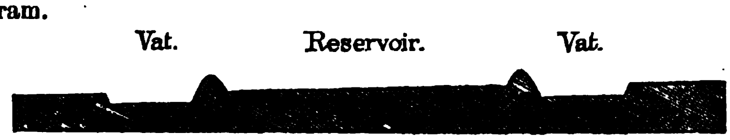

FIG. 54.—Section of Reservoir and Vats at Eagle Salt Works, Nevada.

The lake deposit here is a fine, greenish mud or clay, and is so completely saturated with brine that a thick crust is formed on the surface by efflorescence every dry season. The salt, being supplied from the beds below the surface, is renewed every summer, thus allowing a series of crops to be gathered from the same ground.

A sample of brine from a vat in which the salt had begun to crystallize was analyzed by Mr. Taylor, with the following result:

Specific gravity, 1.2115.

Silica (insoluble)	.0028
Iron and alumina (insoluble)	.0004
Calcium sulphate	.2897
Calcium chloride	.3578
Magnesium chloride	.3787
Potassium chloride	.0023
Sodium chloride	25.3793
Water	73.5890
	100.0000

The annual yield of salt during the past ten years is reported to have been about 2,500 tons. The production has been determined solely by the demand. The amount that could be collected by the simple process of leaching the saline lake-beds and evaporating the saturated waters is practically without limit.

SAND SPRING SALT WORKS.

The most interesting salt field in the Lahontan Basin is situated at the eastern end of a long, barren valley, joined to the Carson Desert on the southeast by a narrow pass, and known as Alkali Valley. The floor of this valley when left dry by the evaporation of Lake Lahontan had the same general level as the Carson Desert, and the lake-beds may be traced through the pass from one desert to the other. In riding from the Carson Desert eastward into Alkali Valley one comes to a line crossing Alkali Valley from north to south beyond which the surface of the desert has a gentle inclination eastward. The surface of the lake-beds when first deposited was horizontal, and the present inclination is due to a fault crossing the valley with a north and south strike, and to

the tilting of the orographic block on which the eastern portion of the valley is situated. The tilting of the floor of the valley resulted in the establishment of a drainage to the eastward for the surface waters, and the formation of a small lake at the eastern end of the valley near Sand Springs. During the winter the water collects there, forming a sheet of brine of variable size, sometimes covering 10 or 15 square miles of surface, but with a depth of only a few inches. In the summer the water evaporates and adds to the layers of salt previously deposited.

The deposit of salt thus accumulated is from 3 to 5 inches thick near the margins, and is said to have a depth in the central portion of the basin of not less than 3 feet. It is gathered by simply shoveling it into barrows and wheeling it out onto firm ground, where it is piled in huge heaps ready for transportation.

The surface of the inclined lake-beds draining to the salt field is absolutely destitute of vegetation, and usually exhibits no saline efflorescence, since this is dissolved away to supply the salt field. Its soil, like that beneath the accumulated salt, is a fine, greenish, saline clay, and may be readily examined in the sides of drainage channels, which score the sloping surface to the depth of 3 or 4 feet.

The method here arranged by nature for dissolving the efflorescent salts from the surface of the lake-beds and evaporating the saline waters in the restricted basin, is practically the same as that employed by man on a smaller scale at the Eagle and Desert Crystal Works.

Associated with the salt obtained at the various salt works are greater or less quantities of the borate of soda and the borate of lime, and in some cases, as at the borax works in Alkali Valley, they attain such importance as to afford a considerable quantity of borax. There are many other localities in the Lahontan Basin where the chloride, the borate, the sulphate, and the carbonate of soda exist, sometimes in large quantities, in the incrustations that form on the deserts, but at present the demand is not sufficient to warrant the working of these deposits for economic purposes.

The chemical study of the desiccation products of Lake Lahontan is far from being completed, but it is safe to say that the vast amount of carbonate of lime sheathing the sides of the basin, and the great quantity of salt impregnating the sediments of the ancient lake, could only have been accumulated by a long process of concentration.

The character of the modern lakes occupying portions of the basin serves to indicate one other element of the physical history of the lake. It is well known, both from laboratory experiments and from the examination of deposits left by the natural evaporation of mineral waters, that the various salts are deposited upon evaporation substantially in the inverse order of their solubility. Their order of deposition is also controlled in part by their relative abundance in the original brine, or, in the case of a lake, by their relative abundance in the waters of the

rivers tributary to it. In a lake that is concentrating by evaporation at the same time that tributaries are bringing in fresh supplies of mineral salts, the first deposit formed is carbonate of lime, this being the least soluble as well as the most abundant of the substances contained in river water; next follows the sulphate of lime; while common salt, which is alike highly soluble and slowly supplied, is stored up for a long time before precipitation commences. Eventually, however, its point of saturation is reached and it begins to crystallize out. The chlorides of magnesium and calcium, and a number of other substances which are more soluble than common salt but less abundant, still continue to increase after the accumulation of salt has reached its limit, and attain their points of saturation only after immense periods of time. These laws are of such wide application that the chemical composition of an inclosed lake gives some basis for the estimation of the time during which concentration has gone on, or at least it affords the means of judging which of two lakes that are without outlet is the older.

Turning now to the Lahontan Basin, and knowing that the old lake underwent a long period of evaporation, while it never filled its basin sufficiently to overflow and thus discharge its saline matter, we should expect to find in the modern lakes of the region, saturated solutions of common salt, with a considerable percentage of the more soluble but rarer minerals. The fact is, however, that none of the present lakes of the Lahontan Basin are highly charged with saline substances, and the proper conclusion appears to be, that they are not remnants left by the evaporation of the ancient great lake. The analyses of the waters of the modern lakes have not been completed, but our reconnoissance has shown that the most of them are sufficiently pure to be drunk by horses and cattle, and even, in case of emergency, by man.

Since Lake Lahontan never rose so as to find outlet, the present freshness of the lakes of its basin cannot be ascribed to a discharge of the saline minerals by overflow, and we seem driven to the conclusion, first suggested by Mr. Gilbert, that the basin has been recently desiccated to dryness and its precipitated salts buried beneath strata of clay and gravel. The chemical history of the lakes thus indicates that the climate of the region, in one of its latest oscillations, was more arid than it is at present.

From the study of the terraces and tufa deposits of Lake Lahontan we learn that the lake had two periods of high water, separated by a time when its basin was even more thoroughly desiccated than it is now, and followed by the present period of aridity. But this evidence fails to show whether the basin ever attained complete desiccation. The unweathered character of the surface of the thinolitic tufa, unlike that of the older lithoid variety, indicates that it was not exposed to subaerial erosion before the dendritic tufa was deposited over it. When the lake reached its second high-water stage it was inhabited by fresh-water gasteropods and conchifers, and it must have attained a certain degree of

freshness. However, since modern lakes, such as Pyramid and Walker, with a degree of salinity distinctly perceptible to the taste, are now inhabited by similar gasteropods, it is not necessary to assign to Lahontan at that stage a high degree of freshness, and it may even have contained in its total volume an amount of saline matter sufficient to produce a highly charged condition when dried away to the relatively small volume corresponding to the deposition of thinolitic tufa. But the discussion of these changes is premature, for there remain many observations not yet thoroughly correlated, and there are many questions to be asked of the lake records during the coming season, the answers to which it is hoped will shed much light on what are now the dark passages of Lahontan history.

LAHONTAN CLIMATE.

Regarding the Lahontan record as a history of climatic oscillations, we learn, first, that there was a time previous to the first flooding of the plains when the basin was at least as arid as at present, and when the alluvial slopes that were afterwards scored by lake terraces were built far into the valleys. The first knowledge we have of the lake is when it formed a gravel embankment across the Humboldt Valley at what is now the southern border of Humboldt Lake, and then, rising higher, cut terraces on the sides of the basin until it reached the Lithoid terrace and stood 500 feet deep over the Carson Desert. This is the record of a moist period. Following it came a time of desiccation, when the lake fell to some point below the present level of Pyramid Lake. Then it rose to the level of the Thinolite terrace and deposited the second sheathing of tufa. This was a time of small precipitation or of moderate aridity. Then followed the period of dendritic tufa, when the lake may be said to have been half filled; and this was succeeded by a brief epoch of still greater precipitation, when the water line was carried to its highest point. Last of all came the evaporation of the water down to its present level, and probably much lower—the final period of aridity.

Thus we find record of three periods of dryness in the history of the basin—a pre-Lahontan, an inter-Lahontan, and a post-Lahontan. There were also two periods of more abundant precipitation, the earlier being longer continued than the later, but the later producing the greater flood.

The curve drawn on page 221 to represent the oscillations of the lake surface may therefore also be used to represent the oscillations of the moisture element in the climate of the basin, and it is here repeated with a different notation as a curve of climate.

The great number of lakes that diversified the surface of the Great Basin during the Quaternary, and even the broad extent of Lakes

Bonneville and Lahontan, does not prove that the climate of that period was excessively humid. When we consider that a great number of the

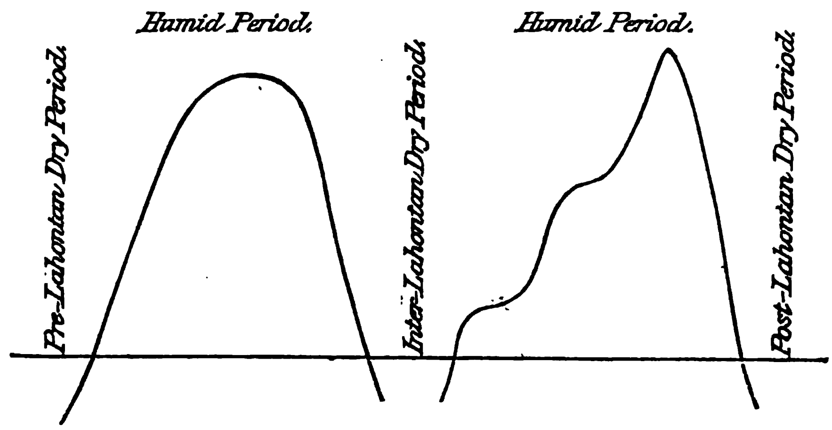

FIG. 55. Curve of Lahontan Climate—Wet *versus* Dry.

inclosed lakes did not overflow, and that this list includes Lahontan, which received the drainage from one flank of the great Sierra, we are forced to admit that the climate could not have approached in humidity that of the basin of the Laurentian lakes, where every lake and almost every pond has its outlet, and where the total discharge constitutes a perennial river of great magnitude. In all probability the ancient climate of Nevada differed less in moisture from its modern climate than from the modern climate of Minnesota.

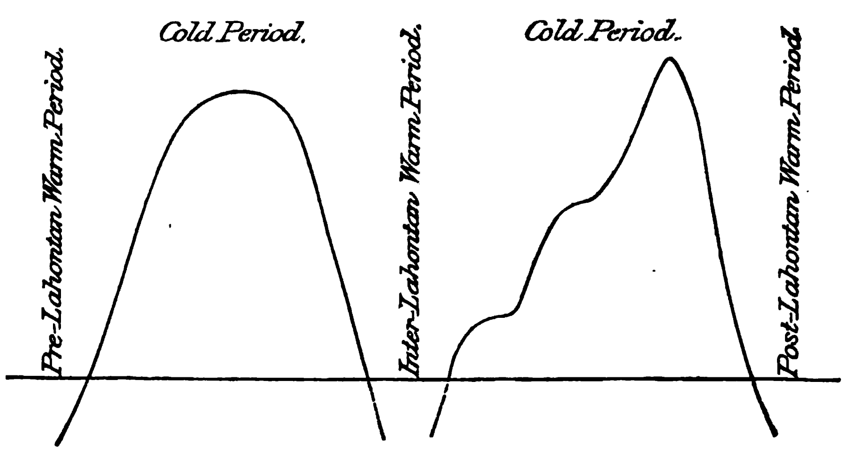

FIG. 56. Curve of Lahontan Climate—Cold *versus* Warm.

Moreover, we have independent evidence in the existence of local glaciers that the Quaternary temperature of the Great Basin was lower than its modern temperature, and since lowering of temperature diminishes evaporation and thus promotes the growth of lakes, it is not even certain that there was in Quaternary time any greater precipitation than

now. The discussion of this question in a quantitative way has not yet been undertaken, but with the facts in hand it seems safe to advance the qualitative hypothesis that the ancient climate of the Great Basin was characterized by very moderate humidity coupled with a low mean temperature and a consequent slow rate of evaporation.

If this view is correct the fluctuations of the lake surface may be interpreted as oscillations of temperature, a low lake corresponding to a high temperature and *vice versa*. Thus construed our curve represents a succession of alternating warm and cold periods, the earlier of the cold periods being of longer duration than the later, and the later being characterized by the lower temperature.

POST-LAHONTAN OROGRAPHIC MOVEMENTS.

Nearly all the valleys that combine to form the basin of Lake Lahontan owe their origin to profound fractures, on the opposite sides of which the rocks have been either raised or lowered to different levels. The displacements in numerous instances have a magnitude of 4,000 or 5,000 feet. Not only did these differential movements produce the lake basin, but their continuance has modified it alike during the existence of the lake, during the inter-Lahontan dry period, and since the final desiccation. There is little doubt that these movements are still in progress, and that the mountains throughout the Great Basin are still slowly rising or being depressed. As a matter of observation we find the evidence of recent faulting best defined along the bases of the highest of the ranges, indicating that these owe their distinction to the fact that they are still growing.

In numerous instances the lines of recent faulting are marked by the presence of hot springs, and so constant is this association that it may be taken as the rule throughout the Great Basin that wherever we find thermal springs we may expect other evidence of recent displacement. The persistence of this relation gives rise to the suggestion that the heat of the hot springs is due to the friction of the rocks along the plane of faulting, or, in other words, to the conversion of motion into heat.

In nearly all cases the recent faults follow old lines of displacement, and they are usually confined to the immediate bases of the mountains, but occasionally, as on the Smoke Creek Desert, one is seen to cross the open plain. The recent fault-scarps divide the alluvial cones that stream down from the mountain valleys, and in numerous instances cut the bars and terraces formed by Lake Lahontan. They range in height from ten feet to fifty or sixty, and sometimes one hundred.

A fault-scarp more recent than the withdrawal of the waters of Lake Lahontan may be traced for more than fifty miles along the western border of the Smoke Creek and Black Rock deserts. Its course is

irregular, varying from a little west of north to northeast, its height seldom exceeds twenty feet, and its line is marked by numerous springs that are either warm or else give evidence of having been thermal during an earlier stage of their existence. The fault at the south end of the Smoke Creek Desert is marked for a long distance by a line of verdure traversing an absolute desert.

Another line of recent displacement occurs on the northeast side of Honey Lake Valley, its course being marked by boiling springs. A third can be traced for fully a hundred miles along the western base of the West Humboldt Range, its scarp in the Lahontan gravels on the eastern border of Humboldt Lake being fully fifty feet in height.

Many other illustrations might be given to show that orographic movements have taken place in very recent times throughout the whole breadth of the Great Basin, and no geologist who examines them can fail to believe that these profound movements of the earth's crust are in progress at the present time.

THE SMALLER FOSSIL LAKES OF THE GREAT BASIN.

The explorations thus far made in the Great Basin, by the geologists of the Fortieth Parallel Survey and by our own corps, have brought to our knowledge fifteen basins (besides those of the great lakes Bonneville and Lahontan) that were occupied by lakes during the Quaternary period. At the present time these valleys are either dry or hold small saline or alkaline lakes. Some of these smaller lakes had outlets and overflowed into lower basins, carving channels of discharge; others were always contained by the barriers that now surround their basins. The valleys that held these minor Quaternary lakes are given in the following list:

Gosiute Valley	Nevada.
Clover and Independence Valleys	Do.
Ruby Valley	Do.
White Pine Valley	Do.
Grass Valley	Do.
Osobb Valley	Do.
Diamond Valley	Do.
Washoe Valley	Do.
Granite Spring Valley	Do.
Mono Valley	California.
Horse Valley	Do.
Madeline Plains	Do.
Pueblo Valley	Do.
Surprise Valley	Do.
Long Valley	Do.

In some of these the evaporating lakes left fields of salt; others, including Surprise, Pueblo, Ruby, and Osobb, still contain shallow lakes. The basins of others are now broad, sage brush valleys, with beach lines about their margins, and with playas in their lowest depressions, which are converted into shallow lakes during wet seasons.

The features that distinguish these valleys from those of the Great Basin that had free drainage during Quaternary times, are marginal lines of sea-cliffs, wave-cut terraces, and wave-built embankments. Usually, too, they are flat-bottomed, the lakes having deposited their sediments in horizontal sheets; and in some instances their sides bear deposits of tufa. In the tufa and the lake-beds the shells of fresh water mollusks are commonly found.

In a valley that has had free drainage for a considerable time the bottom is more or less irregular, sometimes becoming distinctly V-shaped, and it is usually cut by strongly marked lines of drainage. The rim of such a valley is incomplete, and all phenomena due to the action of waves and currents are absent.

Besides the valleys indicated in the preceding list there are others that without doubt held lakes of greater or less size during Quaternary

times, the shore records of which have either been effaced or are too indefinite to be distinguished. These valleys are inclosed basins, and usually have playas at bottom, and in some instances they exhibit incrustations of soda salts. In this class we may group:

Gabbs Valley	Nevada.
Soda Springs Valley	Do.
Fairview Valley	Do.
Virginia Salt Marsh	Do.
Great Salt Basin	Do.
Adobe Meadows	California,

and probably also a large number of the small valleys so numerous throughout central and southern Nevada.